IMPLICATIONS OF COLLISIONS IN SUPERSYNCHRONOUS ORBITS

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ABSTRACT

The current mitigation measure supported and voluntarily practiced in the geosynchronous region (GEO) is to boost satellites into supersynchronous orbits (SSO) in the month or two before stationkeeping fuel is expected to be exhausted. Because this solution does not remove mass from space, some feel that disposal orbits can only be a temporary solution. One concern is the collision hazard between inactive satellites in the SSO region, which raises questions about the consequences of collisions in this regime and possible subsequent interaction with GEO. This paper outlines the methods and tools by which the effects of collisions in the SSO region can be analyzed. The results may help in defining a safe minimum re-orbiting distance above GEO needed to isolate debris from GEO.

1. INTRODUCTION

Since there are no natural sinks for debris in GEO, the accumulation of inactive satellites and other operational debris in this valuable regime has raised particular concern among the many and diverse GEO satellite operators. The practice of raising the altitude of satellites, placing them out of GEO, before stationkeeping fuel is expected to be depleted is mainly for the purpose of maintaining continuous operation, but it is also a cost-effective mitigation measure that many operators are voluntarily implementing. One immediate drawback is that the usage of SSO as a storage area for debris may preclude future plans to utilize it in a more productive manner. However, future technology may allow for different and more permanent mitigation measures for GEO and perhaps even for active removal of debris from GEO and SSO, if the need arises.

In considering the extensive use of SSO for satellite disposal, the first concern is to determine the minimum safe distance above GEO such that objects in the disposal orbits will not interfere with the GEO population in the future. This involves defining the useful GEO area and studying the perturbation effects on objects in SSO. Since there are numerous uncontrolled objects in GEO as well, perturbation analysis for these objects is also relevant. Previous studies have focused on propagating the orbits of intact objects in GEO and SSO. However, in the aftermath of a collision in SSO, pieces of vastly varying sizes and shapes can be found in orbits quite different from the parent objects' orbits. Depending on the altitude of the parent objects in the storage orbits before the breakup, these pieces may be flung into the GEO regime by the impact of the collision, or subsequent perturbing forces over time may cause the pieces to mingle with the GEO population.

2. OUTLINE OF STUDY

The purpose of this paper is to present the methods and tools to study the implications of collisions in supersynchronous orbits. The only results presented are those coming from an extensive literature search; previous studies in the problem of defining the minimum safe re-orbiting distance above GEO are summarized and compared. One part of this study involves using a low-velocity collision model to obtain the typical fragment characteristics and delta-velocities imparted to the fragments. The main work, however, is in conducting an analytic study on the effects of perturbations on the breakup pieces, as well as their effects on the uncontrolled objects in GEO, to determine the extent to which these two populations will intermingle. The varying parameter is the altitude at which the breakup that produced these fragments occurred. From the results, a minimum safe re-orbiting distance above GEO can be proposed, based on the amount of orbit overlap that is deemed to be acceptable. A numeric analysis is also proposed so that the results from each part of the study can be compared. This study is being conducted as part of the primary author's doctoral research.

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3. PREVIOUS WORK

The minimum safe re-orbiting distance above GEO is not a firmly established number, and policies differ among the satellite operators. Various agencies with satellites in GEO have declared their re-orbiting guidelines, including the US Navy, requiring removal by at least 370 km, and the Australian Agency, AUSSAT, specifying re-orbiting capability of up to 1110 km above GEO (Ref. 1). Others have proposed different storage orbits. The Intelsat Board of Governors requires only 40-50 km beyond GEO, while the former Soviet Union supports thrusting to produce large eccentricity (Ref. 2). Some have less specific policies, such as Air Force Space Command, requiring removal to a "safe position" (Ref. 2). Many now support 300 km as the minimum re-orbit distance (Refs. 1,3). Three agencies have published studies leading to their guidelines which are summarized in this paper. These studies mostly have focused on defining the "useful" GEO area and then finding the minimum altitude above it such that debris in the disposal orbit will not likely interact with the GEO population.

3.1 NASA Study

The NASA Safety Standard (Ref. 4) defines the GEO regime as 300 km above and below 35,788 km altitude. The region above 36,088 km altitude is designated as the disposal region for GEO satellites. The Safety Standard and a study by Loftus (Ref. 5) conclude that the perigee altitude should be at least

$$300km + 2{,}000 \times A / m \qquad (1)$$

where the area-to-mass ratio is expressed in m^2/kg. The first term accounts for perturbations at GEO (50 km) and at the disposal orbit (50 km), operational excursions (50 km), imperfect insertion at the disposal orbit (50 km), and a safety margin (100 km). The second term is the varying effects of solar radiation pressure (SRP) which depends on the objects' area-to-mass ratio.

3.2 NASDA Study

NASDA recently updated their guidelines in 1995. The previous policy, which dates from 1985 (Ref. 6), required re-orbiting by 150 km beyond GEO and further specified a desired re-orbiting distance of 500 km. Perturbation studies (Refs. 7-9) led to the first revision:

$$\Delta a = 186km + 0.011 \times a \times C_r \times A / M \qquad (2)$$

where Δa is the re-orbiting distance in km, a is the semi-major axis of the disposal orbit, C_r is the SRP coefficient, A is the effective cross-sectional area, and M is the satellite mass. This equation is explained as follows. 190 km is the sum of the radial variation of a GEO satellite due to all perturbations (Earth oblateness: 35 km, third body, Sun: 53 km, SRP: 45 km; total: 133 km) and the radial variation of a re-orbited satellite due to Earth oblateness (0 km) and solar gravitation (53 km). The entire second term accounts for the effects of SRP on a re-orbited satellite.

This equation has since been revised (Ref. 6). The new expression is

$$\Delta a = 200km + 2 \times 0.011 \times a \times C_r \times A / M \qquad (3)$$

While the 14 km increase in the first term was not explained, the additional factor of 2 in the second term is to account for the long-term variation in the eccentricity vector. The original expression only accounted for the yearly variation in eccentricity vector.

3.3 ESA Study

An ESA study (Ref. 10) suggests radial limits of 50 km above and below geosynchronous altitude to define the boundaries of the geostationary ring. This definition is based on the actual radial variations of controlled satellites in GEO. The initial formula given for calculating re-orbiting distance to null the collision rate over 20 years, as explained further in Ref. 10, is

$$da = 1271A_e + 56km \qquad (4)$$

in which da is the minimum re-orbiting distance above GEO and A_e is the effective area-to-mass ratio. The formula is explained. 1271 A_e accounts for radial variation due to SRP (+/- 928 A_e km) and the coupling effects of SRP and the gravitational forces of Earth and the Moon on the motion of the eccentricity vector (+/- 343 A_e km). The 56 km is the sum of the width of a 0.1 degree ring (37 km) and 19 km to account for the perturbing effects of Earth and the Moon. Recognizing that the eccentricity variation might exceed the aforementioned bounds after 20 years, a final formula with additional buffers is given:

$$da = 1600A_e + 65km \qquad (5)$$

No additional explanation is given to account for this revision.

More recently, Flury (Ref. 11) states that ESA recommends a minimum re-orbiting distance above GEO of 300 km. This number is based on perturbation effects in SSO. The small perturbations, Earth's gravity (J_2, etc.) and third body effects (solar and lunar), cause a +/- 30 km variation while SRP's effect varies with area-to-mass ratio. For A/m [m^2/kg] = 0.1, a conservative value, the total radial variation due to all perturbations is +/- 200 km. Smaller area-to-mass ratios result in smaller variations. Therefore, 300 km is deemed to be enough to account for all perturbations and a 100 km buffer zone.

3.4 Remarks and Comparison

The first impulse is to compare the re-orbiting equations with the flat 300 km recommended distance. For a conservative area-to-mass ratio of 0.1, Loftus's formula gives 500 km as the appropriate distance to re-orbit. The latest NASDA equation gives about 293 km with a = 42,466 km and C_r = 1.0. Loftus's guideline is noticeably more conservative.

Next, compare the individual components of the re-orbiting equations, in particular the perturbation effects, as concluded from these studies. Table 1 summarizes the studies discussed above with A/m $[m^2/kg]$ = 0.1, a = 42,466 km, and C_r = 1.0. Distances are in km.

Study	NASA	NASDA	ESA
Year	1992	1996	1996
GEO Total	50	133	0
Earth's Gravity	N/A*	35	0
Third Body	N/A*	53 (solar)	0
SRP	N/A*	45	0
SSO Total	250	146	200
Earth's Gravity	N/A*	0	30 (Earth, lunar & solar)
Third Body	N/A*	53 (solar)	
SRP	N/A*	93	170
Other	200**	14+	100++
Total	500	293	300

Table 1. Comparison of the re-orbiting equations.

The variations in the figures cited above cannot be easily explained; thus, it is hoped that by undertaking an independent, comprehensive analytic approach complemented with numerical results, a clearer understanding of the effects of perturbations on objects in GEO and SSO can be obtained. The end objective lies in providing more information for the selection of storage orbits. Most notably, the inclusion of SSO breakup modeling and extensive force modeling is highlighted in this study.

4. MODELING LOW-VELOCITY BREAKUPS

Though it is not be the main focus of this study, an important piece of in the problem is the modeling of collisions in the SSO regime. In particular, information on the typical characteristics of and delta-velocities imparted to the fragments produced from non-hypervelocity collisions is desired. Unfortunately, a vast majority of research in impact breakup modeling centers on the hypervelocity collisions associated with objects in low Earth orbits. A few documented GEO studies, however, can be discussed for relevancy to this study.

Long-term evolution programs for GEO generally include non-hypervelocity collision models as a source of debris generation from the on-orbit population. Logically then, this study need not develop an independent model but incorporate the use of an existing model. One such program, developed at the University of Colorado, is ODESI, which includes two non-hypervelocity collision models (Ref. 12). The first is a simplistic spherical model that is statistically-based and assumes that users have good data for the number of fragments produced and the delta-velocities imparted. The second model is a finite element approach, using the general purpose MSC/NASTRAN program in conjunction with MSC/DYTRAN to simulate the dynamic, nonlinear behavior of spacecraft material. The results from this model depend heavily on the grid size employed; fragments produced cannot be smaller than the element grid size. The published study includes results from a 0.5 cm grid, but it is unclear yet whether this is an appropriate mesh size for this study. Moreover, it does not provide the velocities imparted to the fragments.

The velocity imparted to breakup fragments is usually determined using observed data, namely the orbital elements of the generated pieces in the new orbits after the breakup event. In this case, it is unlikely that fragments from GEO or SSO collisions could be detected or tracked. However, if the fragment masses are first determined by a separate method, the velocity distribution can be calculated, using a theory based on the principle of conservation of momentum and energy (Ref. 13).

The decision of whether to work with the above tools has not been made at this time. If another model is deemed to be more suitable, it can be incorporated into subsequent studies

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* Study does not provide the individual contributions to the total perturbation effect.

** Includes operational excursions, imperfect insertion at the disposal orbit, and a safety margin.

+ Unexplained.

++ Safety margin.

5. ANALYTIC STUDY

To determine a suitable storage altitude in SSO, two questions must be considered:

- What is the maximum altitude traversed by typical GEO objects, operational as well as uncontrolled?
- What is the minimum altitude of an object in or ejected in a collision event from the storage orbit?

These concerns can be addressed by examining the equations of motion for a two-body system with perturbations.

Objects in GEO and SSO are heavily influenced by the following perturbations:

- Third-body gravitation, solar and lunar
- Aspherical central body
- Solar radiation pressure (SRP)

An analytic study would aim to determine the maximum radial periodic variations in the objects' orbits.

Equations of motion have been developed for the gravitational effects of Earth's asphericity and nonuniformity in terms of the classic Keplerian elements in the works of Kaula and others (Refs. 14-15). However, in dealing with near-circular and low inclination orbits, such as those of most objects in GEO and the storage orbits, a nonsingular set of orbital elements may be more appropriate. Several works have featured development of the geopotential and third-body gravitational disturbing functions and associated partial derivatives in nonsingular equinoctial elements (Refs. 16-18).

If the objects in GEO and SSO are assumed to be continuously sunlit, the SRP disturbing function takes a form similar to the third-body gravitational affects. This may or may not be a required assumption of the study. Of course, the SRP effects will still depend on the objects' area-to-mass ratio. A likely area-to-mass ratio will be obtained from the satellite collision model.

Two approaches can be taken to determine the maximum periodic effects predicted by the equations of motion. The first is a frequency-independent method in which the amplitudes of the periodic effects from each perturbation are simply summed without regard to the various effects' periodic phasing. Special care must be taken to understand the frequency of the periodics when combining the effects to properly calculate the maximum change in satellite altitude. This approach is the more conservative of the two proposed.

The second method accounts for the phasing differences in the periodic effects. This approach attempts to maximize the radial rate of change by searching over the orbit orientation elements. A symbolic manipulator software package may be invoked to help with the mathematics, if needed. Then, based upon the frequencies and phasing of the periodics, the maximum change in radial amplitude can be deduced.

Once the maximum altitude of GEO objects and the minimum altitude of objects in or ejected from SSO are determined, it will be apparent if the storage altitude is suitable. The altitude of the storage orbit is the parameter to vary as necessary to determine the minimum safe re-orbiting distance above GEO in an iterative manner.

6. NUMERIC STUDY

Validation of the analytic results can be achieved by conducting a numeric analysis using a proven orbit propagator. While special perturbation methods are often the preferred choice for high accuracy numerical studies, they may not be the best choice in this case since the individual periodic effects cannot be easily isolated nor broken down into the short- and long-periodic components. The Draper Semianalytic Satellite Theory (DSST), however, allows for such model tailoring with accuracy comparable to special perturbation methods (Ref. 19). With DSST, the equations of motion are decomposed into the short- and long-periodic contributions with the amount of force modeling configurable at run time (Ref. 20-21). Thus, isolation of the periodic effects is possible. This is an important capability if the results of the analytic study and numerical propagation do not agree.

A second numerical approach to this study can be performed without the analytic portion. In this strictly numeric scenario, a genetic search algorithm can be employed with an orbit propagator to determine the maximum altitude of a GEO object and the minimum altitude of an object in or ejected from the storage orbit. Here, the search algorithm would propagate a set of elements from an element set family prescribed by the GEO and SSO classes to find the orbit orientation that produces the highest and lowest possible altitude, respectively.

Again, special perturbation methods are not the ideal choice here since the propagations will be performed over arcs on the order of 50 years or so. Since DSST numerically propagates averaged equations of motion, much larger time steps, on the order of one day, can be used in the numerical integration. Furthermore, some double-averaging work has been done (Refs. 22-23) which could increase the step size to the order of one year. The short periodic effects are reconstructed using Fourier coefficients and interpolation strategies.

Even with the DSST formulation, the strictly numeric approach would require a lot of computing power. Studies have been performed in which a genetic search algorithm has been coupled with a DSST propagator using high performance parallel virtual machine architecture (Ref. 24) with some success. This may be the most desirable set up if a strictly numerical approach is pursued.

7. CONCLUDING REMARKS

With the proposed extensive use of SSO for storage of GEO satellites after their operative lifetime, careful analysis should be conducted in order to determine the minimum safe distance above GEO such that objects in the disposal orbits will not interfere with the GEO population in the future under any foreseeable circumstances. One possible event is the collision of two objects in SSO which will scatter fragments into orbits that may differ significantly from the parent objects' orbits. This study proposes to examine the ramifications of such a breakup, and this paper describes the methods and tools that are currently being used or under consideration for use.

A low-velocity satellite breakup model that will provide the needed information on the typical characteristics of and delta-velocities imparted to the fragments produced from non-hypervelocity collisions is being sought. This data is needed in the analysis of the effects of perturbations on the collision fragments in their new orbits. Two approaches have been outlined for analytic studies, one of which is a conservative and more simplistic approach where the phasing of the various perturbation effects are not taken into consideration and the amplitudes of the effects are simply summed. The other approach includes analysis on the phasing in determining the maximum change in radial amplitude. The first of the numeric studies described can be performed in conjunction with the analytic work for validation of the results. The second method is an independent, alternative way to approach the problem by a purely numeric path.

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9. REFERENCES

1. Chobotov, V. A., Disposal of Spacecraft at End of Life in Geosynchronous Orbit, *Journal of Spacecraft and Rockets*, Vol. 27, No. 4, 433-437, Jul-Aug 1990.

2. Suddeth, David H., Debris in the Geostationary Orbit Ring, the Endless Shooting Gallery: The Necessity for a Disposal Policy, *NASA Conference Publication 2360*, 349-364, July 1982.

3. National Research Council, *Orbital Debris: A Technical Assessment*, National Academy Press, 2101 Constitution Ave NW, Washington, DC, 20418, 1995.

4. National Aeronautics and Space Administration, *NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris*, NSS 1740.14, Office of Safety and Mission Assurance, Washington, DC, 20546, Aug 1995.

5. Loftus, Joseph P., Orbital Debris Issues in Geosynchronous Orbit, *Summary Minutes of the NASA/DOD Technical Coordination Workshop on Orbital Debris*, 188-200, Colorado Springs, Colorado, Jul 1992.

6. Mori, S., et al., Status of Study on Reorbit Guidelines of Geostationary Satellites in NASDA, *13th Inter-Agency Space Debris Coordination Meeting Proceedings*, WG#4_II-7, Darmstadt, Germany, Feb-Mar 1996.

7. Kato, A., Current Status of NASDA Orbital Debris Mitigation Standards, *Proceedings of the 46th International Astronautical Congress*, IAA.-95-IAA.6.5.02, Oslo, Norway, Oct 1995.

8. Kato, Akira, Current Status of NASDA Space Debris Mitigation Standards, *12th Inter-Agency Space Debris Coordination Meeting Proceedings*, JSA8, Houston, Texas, Mar 1995.

9. Tajima, T., et al., Study of Reorbit for Geostationary Satellites in NASDA, *12th Inter-Agency Space Debris Coordination Meeting Proceedings*, WG4.6, Houston, Texas, Mar 1995.

10. Bird, A. G., et al., An Investigation into the Disposal Orbit for Geostationary Spacecraft, *Space Dynamics*, 65-84, CNES, Nov 1989.

11. Flury, W. and Jehn, R., Minimum Reorbiting Altitude for Geostationary Satellites, *13th Inter-Agency Space Debris Coordination Meeting Proceedings*, WG#4_II-9, Darmstadt, Germany, Feb-Mar 1996.

12. McNamara, Roger P., *The Investigation of Space Debris Generation and Associated Long-Term Effects in the Geosynchronous Region*, Doctoral thesis, Aerospace Engineering Sciences, University of Colorado, 1995.

13. Yasaka, Tetsuo and Ishii, Nobuaki, Breakup in Geostationary Orbit: A Possible Creation of a Debris Ring, *42nd Congress of the International Astronautical Federation*, IAA-91-596, Montreal, Canada, Oct 5-11, 1991.

14. Kaula, William M., *Theory of Satellite Geodesy*, Blaisdell Publishing Co. (Ginn and Co.), Waltham, Massachusetts, 1966.

15. Kaula, W., Development of the Lunar and Solar Disturbing Functions for a Close Satellite, *The Astronomical Journal*, Vol. 67, No. 5, Jun 1962.

16. Cefola, P. J., et al., The Long-Term Prediction of Artificial Satellite Orbits, *AIAA 12th Aerospace Sciences Meeting*, AIAA 74-170, Washington, DC, Jan 30 - Feb 1, 1974.

17. Cefola, P. J., and Broucke, R., On the Formulation of the Gravitational Potential in Terms of Equinoctial Variables, *AIAA 13th Aerospace Sciences Meeting*, AIAA 75-9, Pasadena, California, Jan 20-22, 1975.

18. Cefola, P. J., A Recursive Formulation for the Tesseral Disturbing Function in Equinoctial Variables, *AIAA/AAS Astrodynamics Specialist Conference*, AIAA 76-839, San Diego California, Aug 1976.

19. Cefola, P., et al., Precision Orbit Determination from GPSR Navigation Solutions, AIAA/AAS Astrodynamics Specialist Conference, AIAA-96-3605, San Diego, California, Jul 29-31, 1996.

20. Danielson, D. A., et al., *Semianalytic Satellite Theory (SST): Mathematical Algorithms*, NPS-MA-94-001, Naval Postgraduate School, Monterey, California, 1994.

21. Fonte, D. J., and Sabol, C., Optimal DSST Input Decks for Various Orbit Types, *Phillips Lab Technical Report*, PL-TR-95-1072, Jun 1995.

22. Collins, S. K., *Long Term Prediction of High Altitude Orbits*, Doctoral thesis, Aeronautics and Astronautics, Massachusetts Institute of Technology, Mar 1981.

23. Cefola, P. J., The Long-Term Orbital Motion of the Desynchronized Westar II, *AAS/AIAA Astrodynamics Specialist Conference*, AAS 87-446, Kalispell, Montana, Aug 10-13, 1887.

24. Wallace, S. T., et al., Parallel Orbit Propagation and the Analysis of Satellite Constellations, *AAS/AIAA Astrodynamics Specialists Conference*, AAS 95-428, Halifax, Nova Scotia, Canada, Aug 14-17, 1995.