COLLISION RISK ASSOCIATED WITH INSTABILITY OF MEO DISPOSAL ORBITS

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ABSTRACT

Recent studies show that medium Earth orbit (MEO) disposal orbits, such as those recommended by the U.S. Government Debris Mitigation Guidelines, are unstable, resulting in penetration of the operational constellation by the disposal orbit perigees. The purpose of this study is to obtain an understanding of the associated collision risk posed to the operating Global Positioning System (GPS) constellation. Collision risk was assessed via direct statistical analysis of conjunction miss-distances. Study results include typical time histories of constellation penetration by disposal orbit perigees, estimates of collision risk growth over 200 years for the proposed 832 km disposal orbit, and variation of collision risk with disposal orbit plane and altitude.

1. INTRODUCTION

A number of satellite systems are planned for operation in the orbital region near the 12-hour semisynchronous orbit. This region is commonly referred to as medium Earth orbit or MEO. The Global Positioning System (GPS) and Glonass currently operate in MEO. The proposed European navigation system Galileo may also be deployed in the same region. It has been recommended that satellite systems operating at MEO be moved at end of mission to disposal regions either above or below the 12-hour orbit. As an example, GPS satellites are placed in disposal orbits above the operational constellation. In addition to decommissioned satellites, spent upper stages of Evolved Expendable Launch Vehicles (EELVs) may also be placed into disposal orbits after they serve their mission of inserting future GPS Block IIF replacement vehicles into drift orbits near the targeted mission orbits. The U.S. Government Debris Mitigation Guidelines recommend disposing of vehicles so that the resulting initial orbits clear semisynchronous altitude by +/- 500 km [1].

Studies performed by Gick and Chao [2,3] indicate that MEO disposal orbits can be unstable and undergo significant eccentricity growth over several decades. The disposal orbit perigee can penetrate into the shell of the operational constellation, thereby producing a collision risk for the operating vehicles. Gick and Chao [2] recommended targeting strategies to control the disposal orbit eccentricity growth.

The eccentricity growth is strongly dependent on the initial eccentricity, argument of perigee, and right ascension of ascending node (RAAN, which is orbit plane and disposal epoch-dependent). Fig. 1 shows the maximum eccentricity achieved over 200 years as a function of RAAN for a disposal orbit which has an initial perigee 500 km above the ideal GPS operational orbit, and an initial eccentricity of 0.005. (Throughout this paper, perigee altitudes will be given in terms of height above the ideal GPS operational circular orbit with a radius of 26559.7 km.) In this sample case, the disposal orbit insertion epoch is 1 August 2001. The argument of perigee was selected to maximize the eccentricity growth. From this plot, it is seen that eccentricity growth varies considerably amongst the orbit planes. In extreme cases, the disposal orbits may come close to both low Earth orbit (LEO) and geosynchronous orbit (GEO) operational altitudes. This large eccentricity growth can be attributed to a resonance effect between Sun-Moon perturbations and nodal and apsidal regression caused by the secular component of the J_2 Earth gravitational harmonic.

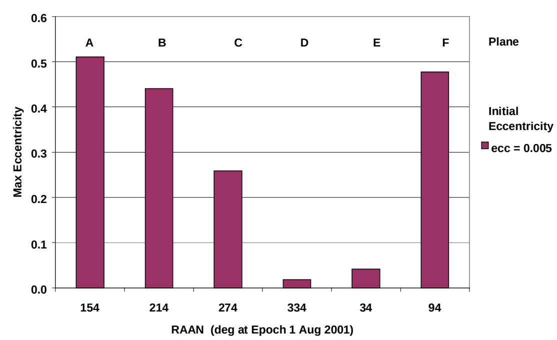

Fig. 1. Maximum Eccentricity Growth Over 200 Years as a Function of RAAN.

Reference [4] presents an analysis by the authors of the collision risk posed to the operational GPS constellation by vehicles disposed in the 500 km perigee disposal orbit. However, GPS operational requirements specify disposal orbit perigee altitudes higher than 500 km. A possible minimum disposal

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km. This orbit perigee would be above the highest expected operational satellite apogee of 730 km, which corresponds to a maximum eccentricity of 0.0275 over mission life. Historically, GPS vehicles have had adequate remaining propellant at end –of-life (EOL) to raise perigee to altitudes between 750 and 1350 km. The current study extends the analysis performed in [4] to include the risk for the 832 km disposal orbit, and to evaluate risk variability with disposal orbit plane and altitude.

2. DISPOSAL ORBIT EVOLUTION

In order to account for the orbital configuration of the constellation over the 200-year time period addressed by this study, the mean elements of 28 operational slots were propagated using the long-term orbit control tool MEANPROP. To model natural orbital evolution, MEANPROP calls the Semi-Analytic Orbit Propagator (SAOP), a program developed by the Charles Stark Draper Laboratory that has undergone extensive validation. All pertinent perturbations were modeled: sun-moon gravity, solar radiation pressure, and an 8×8 WGS84 Earth gravity field. The initial conditions of the vehicle slots were generated from mean element data that was derived from osculating Mission Control Segment (MCS) state vectors dated 2000-8-14 and propagated to an epoch of 1 August 2001. Stationkeeping procedures are carried out in a way that does not affect eccentricity evolution, and hence were not modeled. In order to model the discontinuity in eccentricity of each slot due to the replacement of vehicles at EOL, the eccentricity was periodically rectified back to an initial value of 0.008. As an example, Fig. 2 shows the evolution of eccentricity of constellation slot A5. Fig. 3 shows the constellation altitude histogram, with 50 km bins, derived from the 200 year propagation.

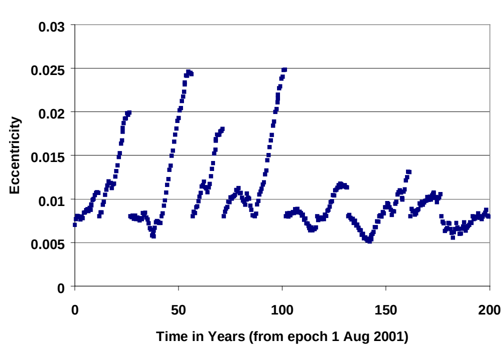

Fig. 2. Eccentricity Growth and Rectification for Vehicle Slot A5 of the GPS Constellation.

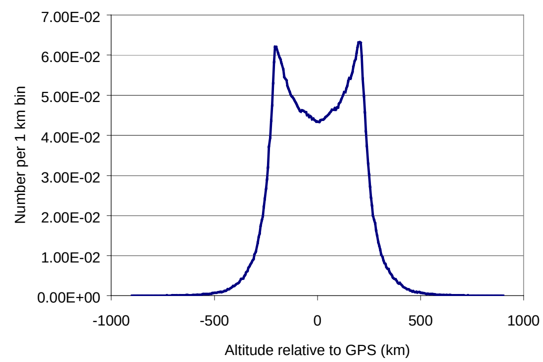

Fig. 3. Average Altitude Histogram of the GPS Constellation (Block IIF orbit) Over 200 Years.

The disposal orbit mean element histories were also computed using MEANPROP. Figs. 4-6 show perigee histories of vehicles disposed on an epoch of 1 August 2001 in Planes C, D, and E (Ω=274, 334, and 34 deg, respectively) at initial perigees of 500 km, 632 km, 832 km, and 1200 km. In each case, the initial disposal orbit eccentricity was selected to be 0.005. The initial argument of perigee was selected to produce the average eccentricity growth scenario. (Eccentricity dependence on argument of perigee is discussed in [2].) In these figures, the constellation bounds are shown by dotted lines.

From Fig. 1, it is seen that Plane C at this epoch exhibits average eccentricity growth, Plane D has minimum growth, and Plane E has the second minimum growth. Fig. 4 shows the perigee evolution for Plane C. It can be seen here that, even though the perigee profiles start at different values, they all pass through the constellation during a relatively small time interval between 80 and 120 years. The perigees of the higher disposal orbits eventually overtake the perigees of the lower disposal orbits. Hence, increasing the initial disposal perigee altitude in Plane C has the effect of delaying the initial penetration of the constellation, but the subsequent penetration through the remainder of the constellation occurs more rapidly, yielding penetration in the same timeframe. Planes A, B, and F have similar perigee profiles.

Fig. 5 shows the perigee evolution for Plane D. Here, eccentricity growth is so slow that increasing initial perigee altitude has a dramatic effect on preventing constellation penetration over 200 years. Fig. 6 shows the corresponding evolution in Plane E. In this case, the eccentricity growth is just large enough to yield significant dwell time in the constellation. Based on fraction of time spent by the disposed vehicle in the constellation, one would expect this scenario to pose the highest collision risk. However, as will be seen in the following, the variation of risk amongst the orbit planes is altitude dependent.

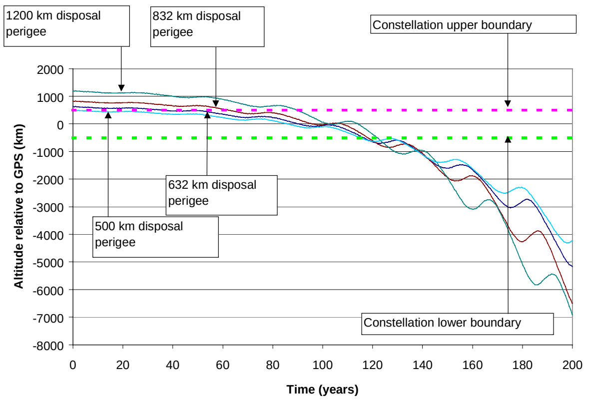

Fig. 4. Altitude Penetration of the GPS Constellation by Disposal Orbits in Plane C.

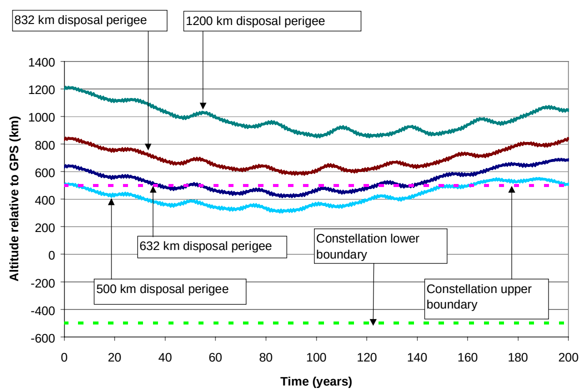

Fig. 5. Altitude Penetration of the GPS Constellation by Disposal Orbits in Plane D.

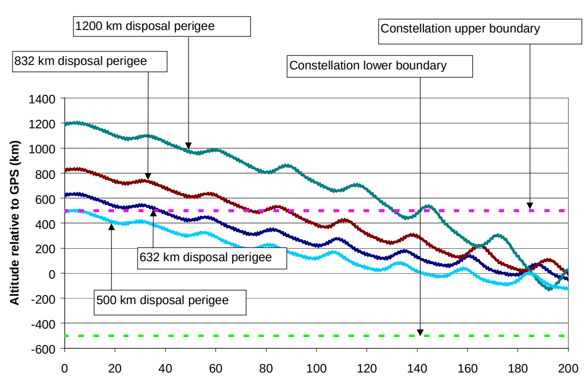

Fig. 6. Altitude Penetration of the GPS Constellation by Disposal Orbits in Plane E.

3. COLLISION RISK FOR DISPOSAL AT 832 KM

To quantitatively assess the collision risk, a statistical analysis of miss distance data was performed. The dominant source of uncertainty in this case is the in-track position of the disposed vehicle relative to the operational vehicle, because the initial argument of latitude at disposal orbit insertion can vary widely depending on disposal epoch and orbit transfer strategy. Hence, the initial argument of latitude is assumed in this study to be uniformly distributed over 360 degrees. The initial conditions of the orbital parameters a, e, i and Ω (semimajor axis, eccentricity, inclination, and RAAN, respectively) are treated deterministically. A value of argument of perigee, ω, is selected which yields the average eccentricity growth given deterministic values of the other orbital elements. The long-term mean orbital evolution was modeled deterministically using MEANPROP.

A simulation was used to compute and collect the miss distances between each disposed vehicle and the 28-member constellation over a period of 200 years. It is shown in [4] that, for a single value of initial relative in-track position, the differences in the mean motions of the disposal and operational vehicles randomize the miss distances. It is then possible to accurately estimate a miss distance probability distribution from a single sample simulation.

Fig. 7 shows a histogram for miss distances between six disposed vehicles at 832 km (one per plane) and the entire 28 member constellation over a 200 year period. The arguments of perigee of the disposed vehicles were selected to yield average eccentricity growth.

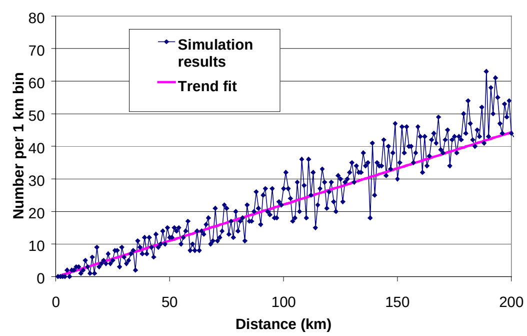

Fig. 7. Miss Distance Histogram Over 200 Years for All 28 Operational Vehicles vs. Six Vehicles (one per plane) Placed in +832 km Disposal Orbits.

Because the histogram exhibits a clear linear trend, the cumulative histogram (i.e., the integral) can be fit with a quadratic form that has a single fit parameter β(T).

$$N(d,T) = [d / \beta(T)]^2 \qquad (1)$$

where N(d,T) is the cumulative number of misses at distance d or less over time period T. Since the miss distance statistics can be modeled with a Poisson process, it is possible to use this equation to directly compute collision probability at small miss distances. This is discussed in more detail in [4] and [5]. The approach is similar to that used in [6].

The average risk of collision between one disposed satellite and all 28 members of the operational constellation is computed from the probability distribution fits for six vehicles, one per plane, by dividing by six. This effectively averages out the dependence on orbital plane ascending node.

The average keepout radius d, assuming random orientation of the two vehicles at collision, was computed from the primary dimensions of the Block IIF and EELV upper stages. Collisions which generate significant amounts of debris were assumed to occur when the vehicle buses come into contact. The corresponding average keepout radius for debris-intensive collisions was estimated to be 3.1 m. Damaging collisions include debris-intensive collisions and the broader set of collisions which generate small amounts of debris but significantly degrade or terminate satellite function. These would include collisions that cause solar array and antenna clipping. The average keepout radius for damaging collisions was estimated to be 4.6 m.

To assess the complete collision risk posed by disposal orbit instability, it is necessary to account for the growth rate of the disposal orbit population. For this analysis, a long-term average replacement rate of 2.24 GPS satellites per year was used. Accounting for both decommissioned GPS vehicles and EELV upper stages, the long-term disposal orbit population rate is then 4.48 per year.

The probability vs. time profile for each newly disposed vehicle is represented by time-shifting the average probability vs. time profile by the difference between the simulation case epoch and the disposal epoch. This generates a series of time-shifted profiles as shown in Fig. 8. At each time point, the total collision risk is then obtained by summing over all the non-zero valued profiles at that time. The resulting overall collision probability over time for the Block IIF design is shown in Fig. 9.

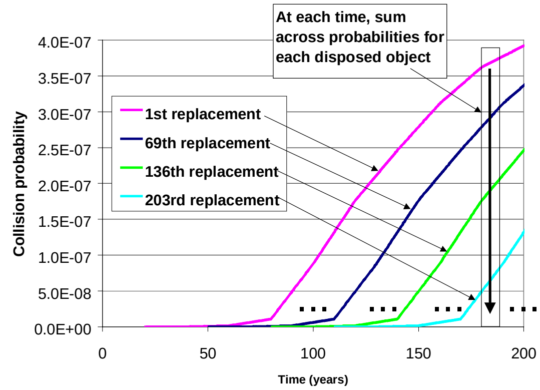

Fig. 8. Generation of the Total Collision Risk due to Disposal Orbit Population Growth.

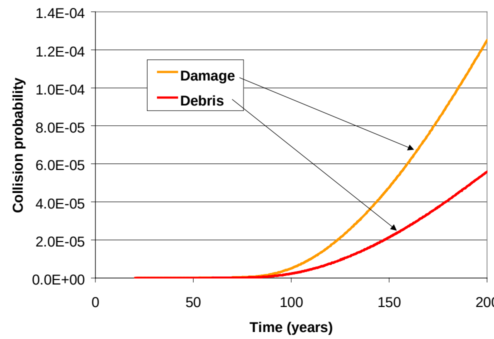

Fig. 9. Collision Risk Posed to a 28 Satellite GPS Constellation by the 832 km Perigee Disposal Orbit Population.

While probability of occurrence of damaging and debris-creating collisions is a desired metric of risk, the keepout radii that are used to compute them are strongly dependent on vehicle design. Over time intervals of decades, the vehicle design will almost certainly change. To overcome this obstacle in obtaining a meaningful estimate of risk to the constellation, it is useful to consider the probability distribution of minimum miss distance over time intervals of interest. This is illustrated in Fig. 10, which shows close approach distances and their likelihood of occurrence. The figure shows that, for the 832 km disposal orbit, close approaches at distances less than a kilometer begin to occur with significant probability (5-50%) between 80 and 120 years. In contrast, close approaches at this level begin between 20 and 60 years for the 500 km disposal orbit [4]. While vehicle dimensions and corresponding collision distances will most likely remain within a few tens of meters, miss distances on the order of several hundred meters could have an operational impact. Currently operating tracking systems would not be able to resolve distances of hundreds of meters. As a result, it may be necessary to either improve tracking accuracy or plan for close approach warnings and maneuvers to assure clearance that is larger than the position knowledge error.

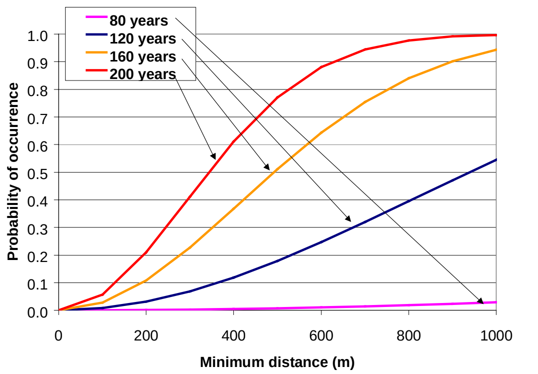

Fig. 10. Likelihood of Close Approach Distances Over Time (Disposal at 832 km).

4. VARIATION WITH ORBIT PLANE AND ALTITUDE

The cumulative risk determined in the previous section was based on a collision risk time profile for each disposed satellite passing through the constellation that was averaged over the six orbit planes. In order to obtain an idea of the accuracy of this approach, the variability of the collision risk amongst the orbit planes was analyzed. Figs. 11 and 12 show the variation with plane of 200-year collision probability for a single disposed vehicle vs. 28 constellation member slots. As would be expected, the risk for the 832 km disposal orbit is lower, mainly due to the delay in constellation penetration.

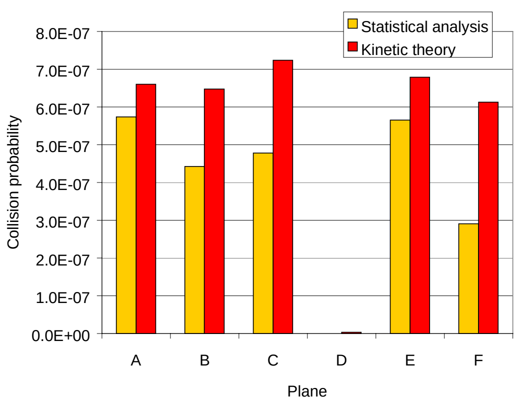

Fig. 11. Probability of Damaging Collisions vs. Constellation Plane, 832 km Disposal Orbit.

The results for the 500 km disposal orbit show the trend that would be expected from the dwell times indicated by the perigee time profiles shown in Figs. 4-6. The risk is highest for Plane E, which has the longest dwell time, and second highest for Plane C, which has the second longest dwell time. Plane D has the lowest risk, since there is minimal constellation penetration. Planes A, B and F have the next lowest risk, because the perigees move rapidly through the constellation between 80 and 120 years. However, the same trend does not hold for the 832 km disposal orbit. The risk in Plane D is still lowest, but the risks in Planes A, B, C, and E are relatively commensurate.

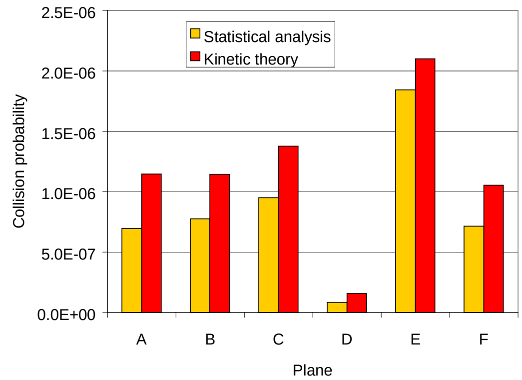

Fig. 12. Probability of Damaging Collisions vs. Constellation Plane, 500 km Disposal Orbit.

As a point of comparison, the results obtained via direct statistical analysis of miss distances were compared with results predicted by kinetic theory. Similar to the theory of molecular gases, this method considers threat objects to be randomly and independently distributed within a given volume of space. For collision probabilities which are much smaller than unity, the following simple formulation can be used,

$$p_c = \int_{I_{tf}} \rho \, \mathrm{v} \, A_{cc} \, dt \qquad (2)$$

where p_c is the collision probability, ρ is the threat object number density, v is the relative velocity magnitude between primary object and threat object averaged over all the threat objects in the local field, A_{cc} is the collision cross-section between the primary and threat objects, and I_{tf} is the cumulative time interval during which the primary object occupies the threat field.

The usual approach for computing density is to assume that the objects are individually distributed throughout toroidal volumes [7-9]. However, it is not clear that this is applicable in the current study. This approach does not take into account the deterministic nature of the ascending nodes for GPS and the existing correlation amongst relative nodal right ascension, argument of perigee, and eccentricity between object pairs for MEO orbits over a period of 200 years [4]. However, planar and the initial values of argument of perigee are randomly distributed throughout the constellation.

For this case, the densities in toroidal shells about the Earth bounded by latitudes of +/- 55 deg were derived from the altitude histogram of Fig. 3. Relative velocities at nodal crossings between orbit pairs were averaged to yield a single mean value of 4.8 km/s. The resulting collision probabilities for a keepout radius of 4.6 m are shown together with the results from direct statistical analysis of miss distances in Figs. 11 and 12. From this, it is seen that the kinetic theory method predicts collision probabilities that are consistently higher by a factor varying between 1.2-2.1. Agreement is better at the lower altitude. This may be due to the fact that the vehicles disposed at 500 km spend more time in the dense regions of the constellation during early orbital evolution, when eccentricity growth rate is still low.

5. CONCLUSIONS

An analysis of the collision risk posed to the operational GPS constellation due to MEO disposal orbit instability was performed. In most orbit planes, eccentricity growth results in eventual penetration of the GPS constellation by disposed vehicles, regardless of selection of initial disposal orbit perigee. Direct statistical analysis of miss distances was used to determine the collision risk over 200 years. Collision risk was shown to decrease with disposal orbit altitude above 500 km. Variation of risk with disposal orbit plane was determined. Results indicate that the collision probability posed to the operational constellation will be low for the next two centuries. However, close approach distances on the order of hundreds of meters will start occurring sooner. This may impact constellation operations, depending on the tracking technology that will be available for the disposed vehicles. Future work will investigate collision warning and maneuver frequency, and also the threat posed by debris resulting from collision between disposed vehicles.

6. ACKNOWLEDGMENTS

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