CONSTELLATION AND "GRAVEYARD" COLLISION RISK FOR SEVERAL MEO DISPOSAL STRATEGIES

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ABSTRACT

A comparison study of three satellite disposal strategies for medium Earth orbit constellations was performed. The study modeled long-term eccentricity growth of the disposal populations. The comparison metrics included collision risk between accumulating disposed satellites (the "graveyard" collision risk), collision risk posed by disposed satellites to operational constellation satellites, and close approaches posed by disposed satellites to operational satellites. The study included the GPS and COMPASS constellations. Results showed that a disposal strategy with initial high initial eccentricity (0.011 to 0.014) and average eccentricity growth significantly reduces global collision risk for GPS and COMPASS combined compared to a strategy that minimizes initial eccentricity.

1. INTRODUCTION

At the end of their operational lives, Global Positioning System (GPS) satellites are boosted into a disposal region above the operational constellation. The GPS program requirement is to move the satellites into a disposal orbit with a perigee that is at least 832 km above the GPS reference orbit radius of 26559.8 km. Recent disposal operations have actually exceeded this requirement. However, due to long-term eccentricity growth, the disposal orbits will eventually spread into the operational altitude range of the GPS constellation and also the other medium Earth orbit (MEO) constellations. This long-term eccentricity growth, which was discovered by Chao [1], is a dynamical resonance condition resulting from the combined gravitational pull of the Sun, Moon, and the non-spherical gravity field of the Earth. The amount of eccentricity growth that occurs is a function of initial disposal orbit elements as well as epoch of disposal [2, 3]. The easiest elements to control are the initial eccentricity and argument of perigee. Current GPS disposal practice is to circularize the disposal orbit as much as possible in order to minimize eccentricity growth, with the goal of delaying intrusion into the operational altitude range. To date, argument of perigee targeting has not been performed, and this would be difficult anyway for an orbit with extremely low eccentricity.

A previous study by Jenkin and Gick [4] considered several alternative disposal strategies. One of the strategies involved restricting initial eccentricity to a low value (in this case to 0.005) and selecting argument of perigee to minimize eccentricity growth. The study showed that this strategy was very effective at minimizing disposal orbit intrusion into the operational constellation for at least 200 years. However, the collision risk between accumulating disposed satellites (the "graveyard" collision risk) was shown to be much higher than the collision risk posed by the disposed satellites to the operational constellation. Collisions between disposed satellites are undesirable due to the potential for generating large amounts of untrackable debris that could spread into the operational altitude range of the constellations due to eccentricity growth. To mitigate this effect, the study introduced the concept of risk dilution by spreading apogee and perigee apart via disposal strategies that result in high eccentricity growth. However, the study did not determine the collision risk between disposed satellites for the high eccentricity growth strategies.

A subsequent study by Rossi [5] considered several disposal strategies. That study evaluated the collision risk between all satellites from three MEO constellations: GPS, GLONASS, and GALILEO. It also computed the collision risk between satellites in the combined MEO and geosynchronous orbit (GEO) populations. One of the cases had a high initial eccentricity of 0.1. The study results showed that the high initial eccentricity strategy reduced collision risk between MEO satellites by an order of magnitude relative to the other, low initial eccentricity strategies that were considered.

The study presented here had two primary objectives. The first objective was to compare several disposal strategies in terms of three metrics: (1) collision risk between disposed satellites, (2) collision risk posed by disposed satellites to operational constellation satellites, and (3) close approaches posed by disposed satellites to operational satellites. Close approaches to

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operational satellites are of interest when collision avoidance is being practiced. Collision avoidance maneuvers would interrupt the navigation function of a satellite.

The second objective of this study was to include both GPS and COMPASS (Beidou-2) in the study. (GLONASS and GALILEO will be included in future work.) Current publicly-available information indicates that COMPASS will be deployed between GPS and GALILEO. There presently is one operational Beidou-2 satellite with a semi-major axis altitude of 21532 km (per the U.S. STRATCOM unclassified catalog of resident space objects), which is 1350 km above the GPS reference orbit.

2. DISPOSAL STRATEGIES

Three disposal strategies were considered in this study. All three were selected to require similar orbit transfer effort (ΔV) for each constellation.

The first strategy is referred to as the "baseline." For GPS, the perigee was fixed at 832 km above the GPS reference orbit. The eccentricity was randomly selected from a Gaussian distribution with mean 0.002119 and standard deviation 0.001358. These values were derived from data in the 2005 Week 41 U.S. STRATCOM catalog for 12 GPS Block II disposed satellites. Argument of perigee was randomly selected from a uniform distribution. This strategy is intended to represent current GPS disposal practice. For COMPASS, the perigee was fixed at 300 km above the COMPASS reference orbit. This selection assumes that COMPASS disposal practice will mirror GALILEO disposal practice, for which 300 km has been cited in various studies. The eccentricity and argument of perigee are selected the same as for GPS.

The second strategy is referred to as "high e_0 case 1." For GPS, the semi-major axis is fixed at the mean value for the baseline strategy (27449.97 km). The initial eccentricity (e_0) is fixed at 0.014, which is considered high relative to the eccentricity for the baseline case. This yields a perigee just 500 km above the GPS reference altitude, and an apogee just below the COMPASS lower boundary. The argument of perigee is then selected to minimize eccentricity at the earlier of (1) 50 years after disposal, or (2) at the end of the disposal orbit propagation interval (January 1, 2210). The intent of this strategy is to maximize the initial apogee-perigee spread between the two constellations without causing initial overlap, but to restrict eccentricity growth for at least 50 years. The idea is to reduce the collision risk between disposed satellites but also delay entry of the disposed satellites into the operational constellations. For COMPASS, the semi-major axis is fixed at the mean value for the baseline strategy (28270 km). The initial eccentricity is fixed at 0.011. This yields a perigee just 50 km above the COMPASS reference altitude. Argument of perigee is selected in the same way as for GPS.

The third strategy is referred to as "high e_0 case 2." This strategy is the same as "high e_0 case 1" except that argument of perigee was randomly selected from a uniform distribution to represent untargeted arguments of perigee. This will yield a mixed low and high eccentricity growth strategy.

3. GENERATION OF INITIAL CONDITIONS

The study simulated a sequence of disposal of satellites and the replacement of operational satellites. The start date of the simulation was January 1, 2010. It was assumed that both the GPS and COMPASS constellations are fully populated with operational satellites. The GPS constellation model included 28 satellites in six orbit planes, each with an inclination of 55° and a semi-major axis of 26559.8 km (altitude of 20181.7 km). The COMPASS constellation model included 30 satellites in three orbit planes, each with an inclination of 55° and a semi-major axis of 27910.137 km (altitude of 21532 km).

The GPS constellation replenishment period was 11.15 years. This results in one new operational satellite and one disposed satellite every 145 days. The COMPASS constellation replenishment period was 8 years. This value is based on a stated 8-year design life on the website SinoDefence.com. This results in one new operational satellite and one disposed satellite every 97 days.

For a given replenishment cycle, the orbit plane (hence RAAN) sequence is randomly selected but constrained to yield repopulation of the constellation. The same orbit plane sequence is then repeated each replenishment cycle.

The disposal orbit inclination was randomly selected from a Gaussian distribution with mean 55° and standard deviation 1.247213°. The standard deviation value was computed from the same U.S. STRATCOM catalog data for 12 disposed GPS satellites used to compute the eccentricity mean and standard deviation for the GPS baseline disposal case. This inclination dispersion is modeled because the long-term eccentricity growth is sensitive to the initial inclination.

The currently existing MEO disposal population and future upper stages were not included. These populations will be included in future work.

4. LONG-TERM ORBIT PROPAGATION

The Aerospace Corporation tool MEANPROP was used to perform the long-term propagation of the constellation and disposal orbits. MEANPROP is a mean orbit element control simulation that uses the Semi-Analytic Orbit Propagator (SAOP) to perform long-term propagation. SAOP is a program developed by the Charles Stark Draper Laboratory that has undergone extensive validation [6]. In this study, the force model included Sun-Moon gravity, an 8 × 8 WGS84 Earth gravity field, solar radiation pressure, and atmospheric drag. For modeling the effect of solar radiation pressure, area and mass values were based on the GPS IIF satellite, and the reflectivity coefficient c_r was assumed to be 1.3. For modeling the effect of atmospheric drag, the MSIS-90 atmosphere model was used, but this only affected a small number of disposal orbits with very high eccentricity growth.

The disposal orbits were propagated from time of satellite disposal to January 1, 2210. The operational satellite orbits were propagated from time of disposal of the replaced satellite to the end of the replenishment period. For GPS, the eccentricity was reset to 0.008. For COMPASS, the eccentricity was reset to 0.000717. This value was taken from 2008 Day 339 U.S. STRATCOM data on Beidou-2.

Figure 1 shows the apogee and perigee altitude evolution for GPS disposed satellites for the baseline case. It is seen that, in spite of the low initial eccentricity, eccentricity growth still occurs. Figure 2 shows the same plot for GPS disposed satellites for high e_0 case 1. It is seen that the apogee-perigee spread initially spans the gap between the GPS and COMPASS operational ranges, but then the spread contracts until shortly after 100 years (after January 1, 2010), when it flares out. Figure 3 shows the same plot for GPS disposed satellites for the high e_0 case 2 disposal strategy. It is seen that there is a mixture of apogee-perigee spreading patterns. Some orbits follow the high e_0 case 1 pattern, while others exhibit moderate to aggressive eccentricity growth. The highest eccentricity growth orbits experience more eccentricity growth than the highest eccentricity growth orbits for the baseline strategy. Hence this strategy offers some high eccentricity growth without requiring the extra effort of argument of perigee targeting. Of course it will not yield as much eccentricity growth across all disposed satellites as can be obtained with argument of perigee targeting. Figures 4-6 show the corresponding apogee-perigee altitude evolution plots for COMPASS. The same eccentricity growth patterns are observed as for GPS, respectively for each disposal strategy.

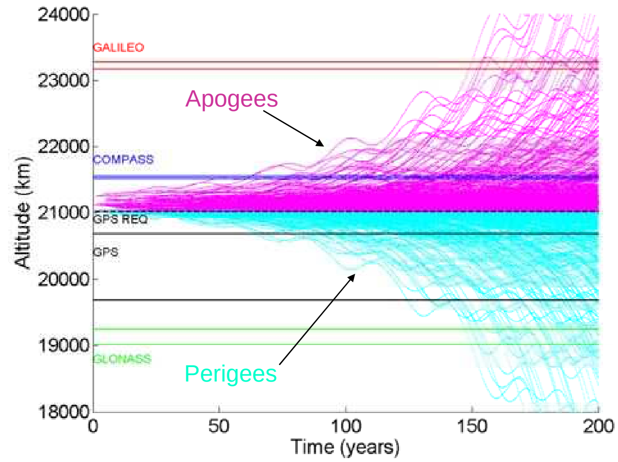

Figure 1. Apogee-perigee altitude evolution for GPS disposed satellites, baseline disposal strategy.

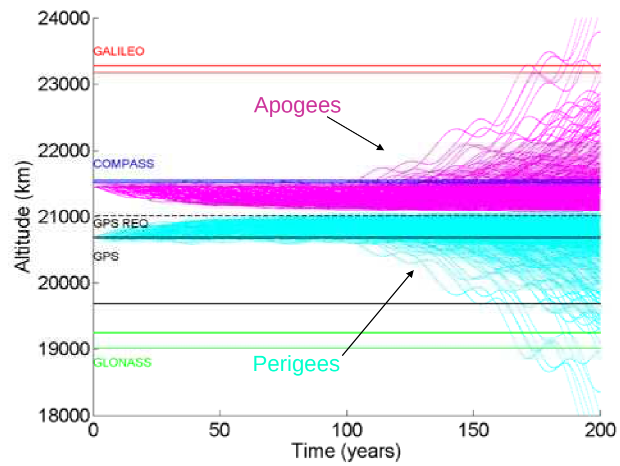

Figure 2. Apogee-perigee altitude evolution for GPS disposed satellites, high e_0 case 1 disposal strategy.

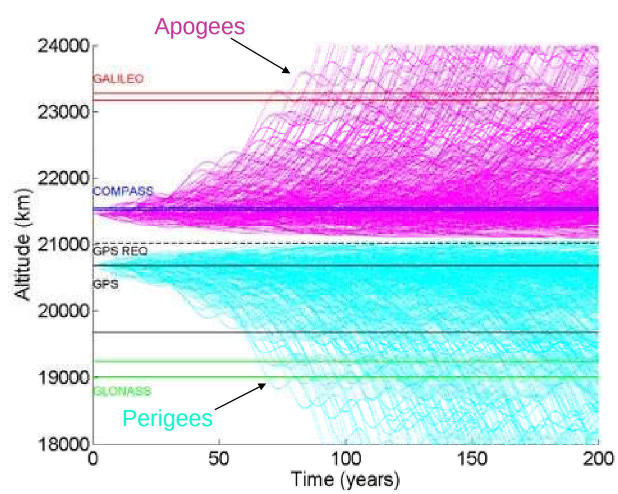

Figure 3. Apogee-perigee altitude evolution for GPS disposed satellites, high e_0 case 2 disposal strategy.

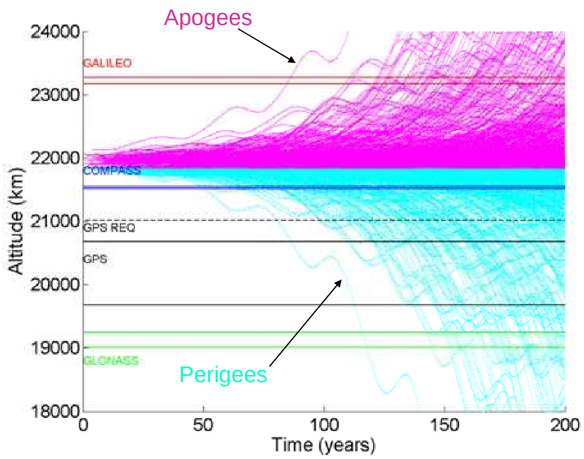

Figure 4. Apogee-perigee altitude evolution for COMPASS disposed satellites, baseline disposal strategy.

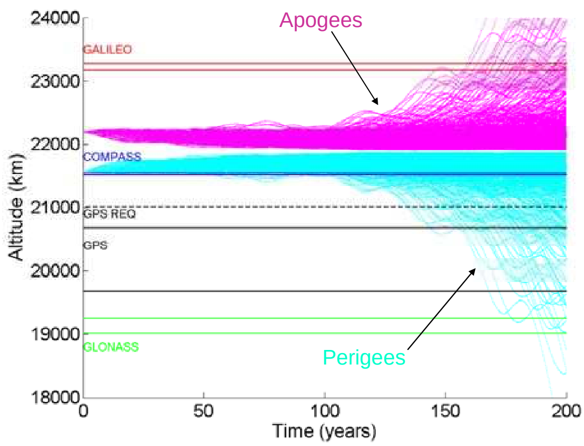

Figure 5. Apogee-perigee altitude evolution for COMPASS disposed satellites, high e_0 case 1 *disposal strategy.*

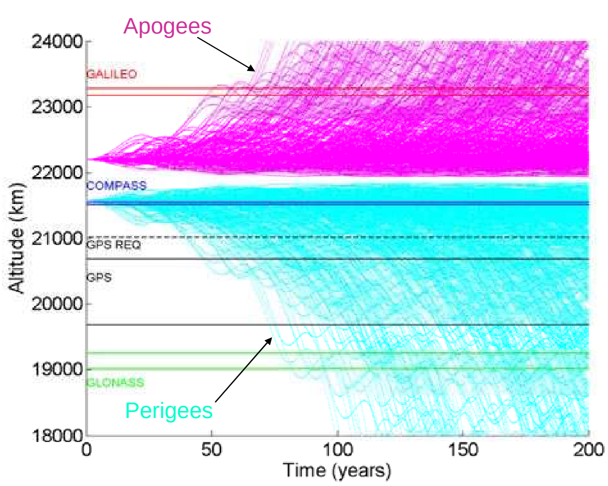

Figure 6. Apogee-perigee altitude evolution for COMPASS disposed satellites, high e_0 case 2 *disposal strategy.*

5. COLLISION RISK AND CLOSE APPROACH METHODOLOGY AND VALIDATION

To determine long-term collision risk and close approaches, an orbit trace crossing and proximity method was used. An orbit trace is defined as the locus of points on a Keplerian orbit. As the orbits of the various disposed and operational satellites evolve, their mean orbit traces will eventually cross or come within proximity of each other. In this method, a collision is only considered possible if the orbit traces cross each other. For each pair of objects, all the orbit trace crossings during the risk assessment time interval are determined. At each orbit trace crossing, the probability that the two objects will pass within a specified collision radius is determined using an analytical formulation. The collision probabilities at all the orbit trace crossings are then summed together to yield the total. If the direct sum is close to unity (e.g., > 0.2), then the individual probabilities are combined by passing the sum through a Poisson distribution, which is accurate as long as the individual probabilities are much less than unity (always the case for satellites of practical size).

For close approaches, an extension of this method is used to accommodate a much larger intrusion radius. For each disposed and operational satellite pair, all time intervals when the operational satellite and disposal orbit traces are within a close approach threshold distance of each other are determined. It is not required that the orbit traces cross during these intervals. For each time interval, the probability that the two objects will pass within the close approach radius is determined using a semi-analytical method. The close approach probabilities for all the time intervals are then summed to yield the average number of close approaches during the assessment time interval. Details of this method will be presented in a future paper.

The advantage of this method is that it accounts for knowledge of the right ascension of ascending node (RAAN) and argument of perigee of the disposal and operational orbits being considered. It avoids the bin storage requirements for storing spatial density and relative velocity that would be associated with a high resolution flux method.

To assess the accuracy of this method, a comparison with a miss distance method was performed. In the miss distance method, a detailed conjunction simulation was performed over 200 years, and the resulting miss distances in 20-year intervals were binned into histograms and fit with linear trends. The collision risk for each 20-year interval was then determined by evaluating the linear trend fit at the collision radius. Since the linear trends fit the detailed conjunction simulation data very well, this method was considered the benchmark. However, it is very computationally intensive.

A GPS disposal case taken from [7] was selected. In this case, six vehicles are disposed at 500 km, one in each constellation plane. These vehicles subsequently penetrate the GPS constellation due to orbital eccentricity growth. Using each method, time profiles of collision probability posed by each disposed vehicle to the GPS constellation over 200 years were computed and then averaged together into a single profile. The averaged profiles resulting from the two methods are presented in Fig. 7. The plot shows that the orbit trace crossing method agrees very well with the miss distance method. However, the orbit trace crossing method is computationally much faster.

The plot also shows curves for two variants on a spatial density-based method that assumes that RAAN and argument of perigee are uniformly distributed. The density field represents the GPS constellation, and varies with altitude. One curve accounts for density variation over latitude, while the other is based on the average density over latitude. Both curves are based on a fixed average relative velocity in the flux computation. It is seen that both curves over-predict the collision risk relative to the miss distance and orbit trace crossing methods. It should be pointed out that a flux method based on high-resolution spatial and temporal binning of spatial density and relative velocity may yield better agreement.

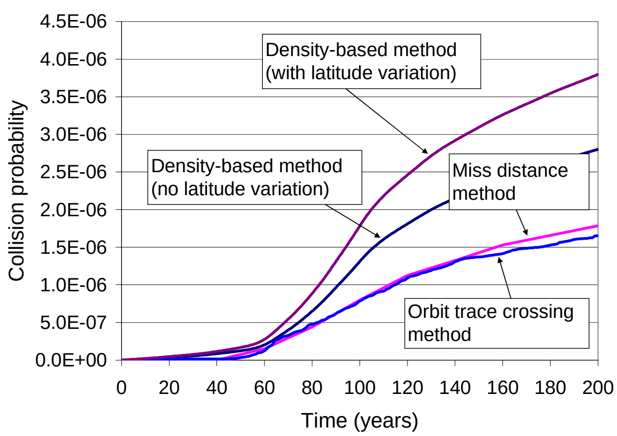

Figure 7. Comparison of methods for computing collision risk. Results are for a GPS disposal case taken from [7].

In the present study, collision probability was evaluated for an average collision radius of 7.4 m. This collision radius is the average distance between two touching GPS IIF satellites. Results for a different collision radius can be obtained by scaling the collision probability by the ratio of the squares of the collision radii.

The close approach radius was set to 3.1 km. This is a very rough attempt to represent special perturbations propagation errors. The value was obtained by taking the 3-sigma error ellipsoid for two-line element sets in the GPS orbit regime from The Aerospace Corporations's COVGEN model, averaging over encounter directions, and dividing by three. It is assumed that close approaches within this distance will induce significant operator workload and potential outage of the satellite due to an avoidance maneuver.

6. COLLISION RISK RESULTS

Figure 8 shows the cumulative collision probability between disposed satellites over time for the baseline disposal strategy. The plot contains four curves that show (1) collision probability between GPS disposed satellites only, (2) collision probability between COMPASS disposed satellites only, (3) cross-collision probability between GPS disposed satellites and COMPASS disposed satellites, and (4) the total collision probability between combined GPS and COMPASS disposed satellites, which is the sum of the first three collision probabilities. It is seen from the plot that cross-collision risk between GPS disposed satellites and COMPASS disposed satellites is much lower than the risk among GPS disposed satellites only and the risk among COMPASS disposed satellites only. This shows that the total risk is determined by confinement of each separate disposal population, and not by mixing between the two populations. The total combined collision risk is 2.4% after 100 years and 12.6% after 200 years.

Figure 9 shows the same plot but for the high e_0 case 1 disposal strategy. As for the baseline disposal strategy, the total risk is determined by confinement of each separate disposal population, and not by mixing between the two populations. However, the high initial eccentricity has resulted in a reduction in the total combined collision risk, which is now 1.3% after 100 years and 7.7% after 200 years.

Figure 10 shows the same plot but for the high e_0 case 2 disposal strategy. In this case, the cross-collision risk between GPS disposed satellites and COMPASS disposed satellites is between the risk among GPS disposed satellites only and the risk among COMPASS disposed satellites only. This shows that contributions to the total risk by confinement of each separate disposal population and by mixing between the two populations are comparable. The plot shows that the combination of high initial eccentricity and accelerated eccentricity growth for some disposal orbits has resulted in a significant reduction in the total combined risk, which is now 0.54% after 100 years and 2.9% after 200 years. Figure 11 shows the cumulative collision probability between combined GPS and COMPASS disposed satellites over time for all three disposal strategies.

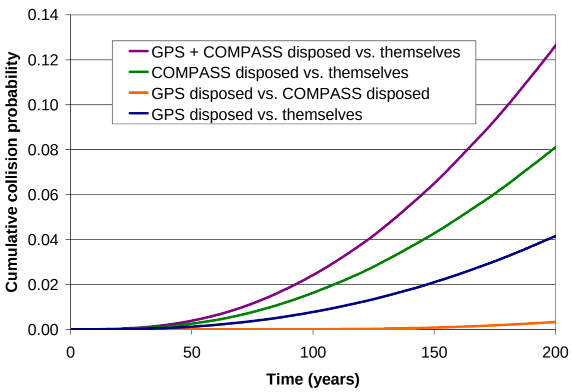

Figure 8. Cumulative collision risk between disposed satellites over time for the baseline strategy.

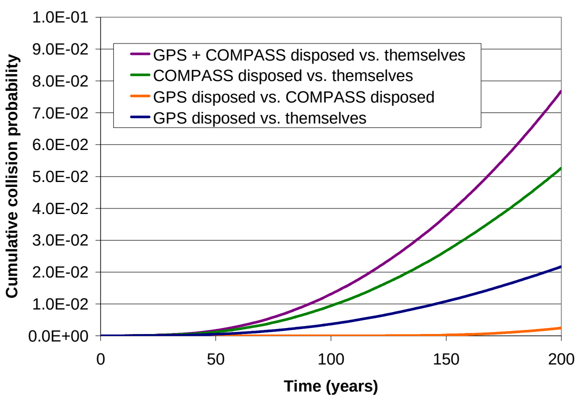

Figure 9. Cumulative collision risk between disposed satellites over time for the high e_0 case 1 strategy.

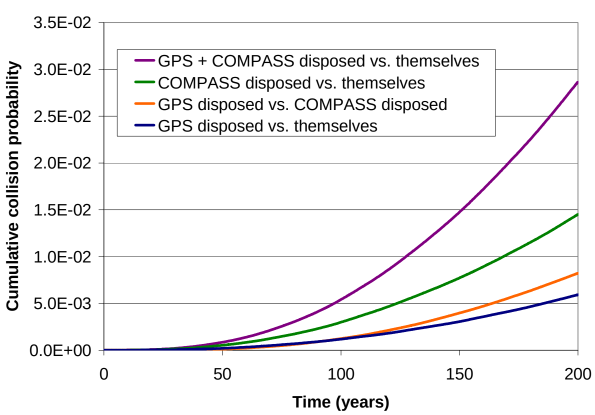

Figure 10. Cumulative collision risk between disposed satellites over time for the high e_0 case 2 strategy.

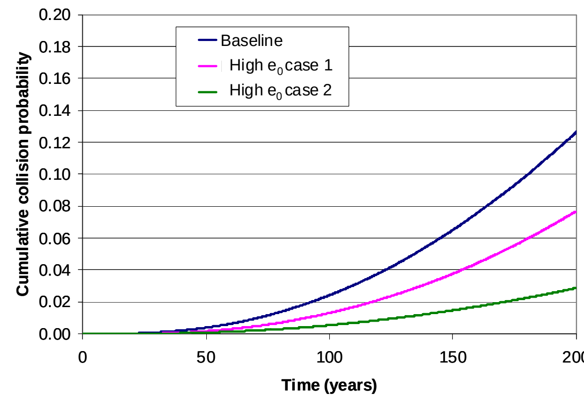

Figure 11. Cumulative collision risk between combined GPS and COMPASS disposed satellites over time for all three disposal strategies.

Figure 12 shows the total cumulative collision probability posed by combined GPS and COMPASS disposed satellites to GPS operational satellites for all three disposal strategies. For comparison, the total cumulative collision probability between combined GPS and COMPASS disposed satellites is shown on the same plot. It is seen that the collision risk between disposed satellites is higher than collision risk posed to operational satellites by at least one to three orders of magnitude, depending on disposal strategy, and therefore dominates global MEO collision risk.

The high e_0 case 2 disposal strategy significantly decreases the collision risk between disposed satellites relative to the baseline strategy. This strategy increases the total collision risk posed to the GPS operational satellites, but that collision risk is still approximately 1.7 orders of magnitude below the collision risk between the disposed satellites.

The high e_0 case 1 disposal strategy yields only a small reduction in collision risk between disposed satellites relative to the baseline strategy. However, it also decreases the total collision risk posed to the GPS operational satellites. This decrease in collision risk is attributable to the superior confinement performance of combining high initial eccentricity with argument of perigee targeting over simply minimizing initial eccentricity and not targeting argument of perigee.

Figure 13 shows the same plot as in Fig. 12, but for the COMPASS operational satellites. The high e_0 case 2 disposal strategy increases the total collision risk posed to the COMPASS operational satellites relative to the baseline strategy, but that collision risk is still approximately one order of magnitude below the collision risk between the disposed satellites. It is also seen that high e_0 case 1 disposal strategy yields approximately the same long-term collision risk posed to the GPS operational satellites as the baseline strategy, although it poses a higher near-term risk. This increase in near-term collision risk is attributable to the fact that the COMPASS initial disposal orbit perigee in the high e_0 case 1 disposal strategy is very close to the narrow altitude range of the COMPASS constellation that was assumed in this study.

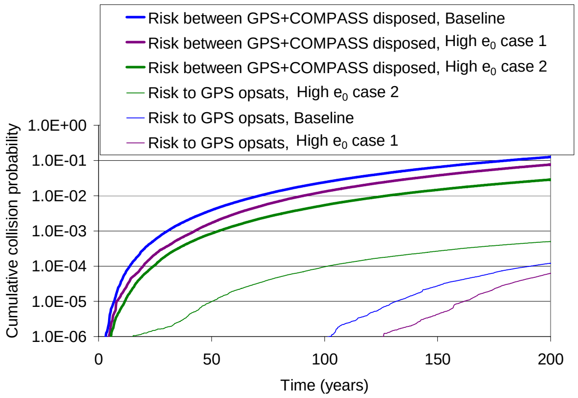

Figure 12. Comparison of total collision risk between combined GPS and COMPASS disposed satellites with total collision risk posed to GPS operational satellites for all three disposal strategies.

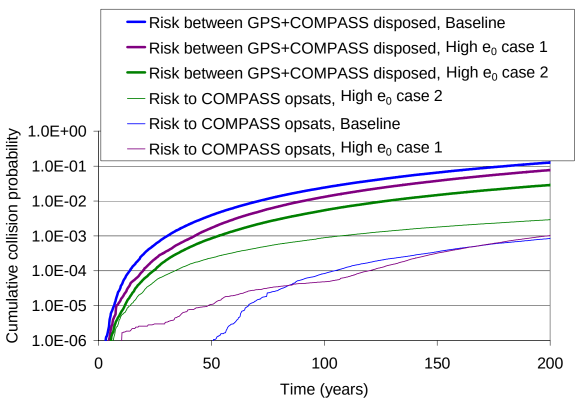

Figure 13. Comparison of total collision risk between combined GPS and COMPASS disposed satellites with total collision risk posed to COMPASS operational satellites for all three disposal strategies.

7. CLOSE APPROACH RESULTS

Figure 14 shows cumulative close approaches posed by combined GPS and COMPASS disposed satellites to GPS operational satellites for all three disposal strategies. Figure 15 shows the same plot but for close approaches to COMPASS operational satellites. The close approach files show a similar trend as the collision probability profiles. For all combinations, the high e_0 case 2 disposal strategy yields more and earlier close approaches than the baseline strategy. The high e_0 case 1 strategy yields fewer close approaches to GPS operational satellites than the baseline strategy. This strategy yields approximately the same number of close approaches to COMPASS operational satellites as the baseline strategy.

It is also seen that the COMPASS constellation experiences more close approaches by both COMPASS disposed satellites and GPS disposed satellites than the GPS constellation for all three disposal strategies. The average close approach frequency posed by combined GPS and COMPASS disposed satellites to COMPASS operational satellites for the high e_0 case 2 strategy is approximately one every four months after 20 years, whereas for GPS it is approximately one every 1.7 years after 35 years. This result is caused by COMPASS' low disposal orbit altitude relative to the constellation reference altitude (300 km), as well as by its narrow operational altitude range (~100 km), both of which were assumed for this study.

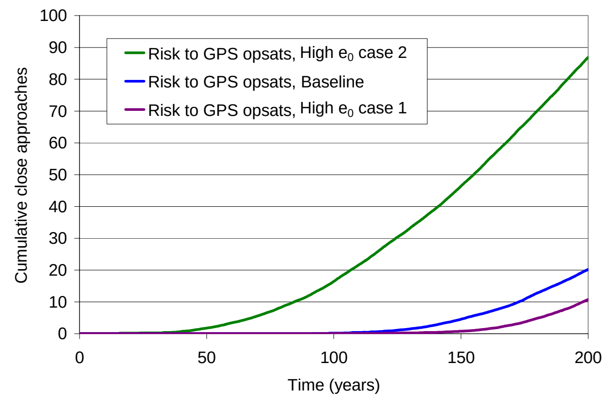

Figure 14. Close approaches within 3.1 km posed by combined GPS and COMPASS disposed satellites to GPS operational satellites for all three disposal strategies.

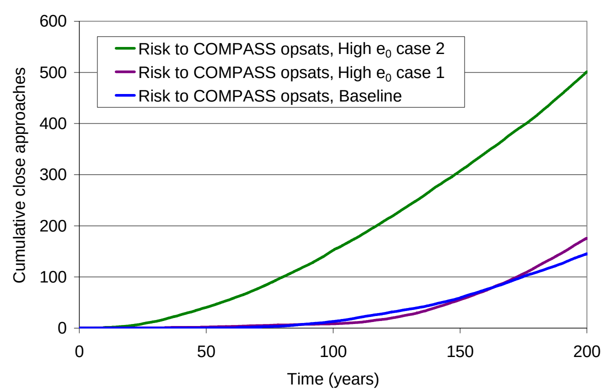

Figure 15. Close approaches within 3.1 km posed by combined GPS and COMPASS disposed satellites to COMPASS operational satellites for all three disposal strategies.

8. CONCLUSIONS

This study considered three different disposal strategies for the GPS and COMPASS constellations. Study results showed that long-term collision risk between disposed satellites is higher than collision risk posed to operational satellites by at least one to three orders of magnitude, and therefore dominates global MEO collision risk.

The high e_0 case 2 disposal strategy significantly reduced the collision risk between disposed satellites relative to the baseline disposal strategy (which represents current GPS disposal practice) for similar ΔV cost. The collision risk reduction within the separate GPS and COMPASS disposal populations outweighed the increase in cross-risk between the two populations. The disadvantage of this disposal strategy is an increase in close approaches to operational satellites.

The high e_0 case 1 disposal strategy yielded only a small reduction in the collision risk between disposed satellites relative to the baseline disposal strategy. However, this strategy decreased the close approaches to operational satellites relative to the baseline strategy. Therefore a disposal strategy with high initial eccentricity combined with argument of perigee targeting is superior for confinement than a strategy that simply minimizes initial eccentricity and does not target argument of perigee.

The COMPASS operational satellites experienced more close approaches than the GPS operational satellites for all three disposal strategies. This result is due to COMPASS' lower disposal orbit altitude relative to the constellation reference altitude, and its narrower operational altitude range, both of which were assumed for this study.

Refinements to these disposal strategies may offer further improvement in the trade-off between global collision risk and close approaches posed to operational satellites.

9. ACKNOWLEDGMENTS

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