OPERATIONAL IMPACT OF IMPROVED SPACE TRACKING ON COLLISION AVOIDANCE IN THE FUTURE LEO SPACE DEBRIS ENVIRONMENT

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Abstract

Even if global space policy successfully curtails on orbit explosions and ASAT demonstrations, studies indicate that the number of debris objects in Low Earth Orbit (LEO) will continue to grow solely from debris on debris collisions and debris generated from new launches. This study examines the threat posed by this growing space debris population over the next 30 years and how improvements in our space tracking capabilities can reduce the number of Collision Avoidance (COLA) maneuvers required keep the risk of operational satellite loss within tolerable limits. Particular focus is given to satellites operated by the Department of Defense (DoD) and Intelligence Community (IC) in Low Earth Orbit (LEO). The following debris field and space tracking performance parameters were varied parametrically in the experiment to study the impact on the number of collision avoidance maneuvers required:

- Debris Field Density (by year 2009, 2019, 2029, and 2039)
- Quality of Track Update (starting 1 sigma error ellipsoid)
- Future Propagator Accuracy (error ellipsoid growth rates - Special Perturbations in 3 axes)
- Track Update Rate for Debris (stochastic)
- Track Update Rate for Payloads (stochastic)

Baseline values matching present day tracking performance for quality of track update, propagator accuracy, and track update rate were derived by analyzing updates to the unclassified Satellite Catalog (SatCat). Track update rates varied significantly for active payloads and debris and as such we used different models for the track update rates for military payloads and debris.

The analysis was conducted using the System Effectiveness Analysis Simulation (SEAS) an agent based model developed by the United States Air Force Space Command's Space and Missile Systems Center to evaluate the military utility of space systems. The future debris field was modeled by The Aerospace Corporation using a tool chain which models the growth of the 10cm+ debris field using high fidelity propagation, collision, and breakup models. Our analysis uses Two Line Element (TLE) sets and surface area data generated by this model sampled at the years 2019, 2029, and 2039. Data for the 2009 debris field is taken from the unclassified SatCat. By using Monte Carlo simulation techniques and varying the epoch of the military constellation relative to the debris field we were able to remove the bias of initial conditions. Additional analysis was conducted looking at the military utility impact of temporarily losing the use of Intelligence Surveillance and Reconnaissance (ISR) assets due to COLA maneuvers during a large classified scenario with stressful satellite tasking. This paper and presentation will focus only on unclassified results quantifying the potential reduction in the risk assumed by satellite flyers, and the potential reduction in Delta-V usage that is possible if we are able to improve our tracking performance in any of these three areas and reduce the positional uncertainty of space objects at the time of closest approach.

Keywords: Orbital Debris, Conjunction, Collision Avoidance, Future Debris Field

1. IMPETUS

The on orbit collision of Iridium-33 and Cosmos-2251 provided a stark reminder that mission critical satellites can suddenly be lost in a collision. Large spikes in the tracked orbital debris population associated with this collision, the Chinese ASAT demonstration and the USA-193 shoot down have further heighted our sensitivity to the growing risk of collision. The U.S. Air Force has begun exploring possible system concepts that would provide an active debris removal capability. However before any of these concepts can be developed further there is a need to assess how our ability to operate in LEO will be impacted by future debris. This study was conducted to perform that assessment.

2. GOALS

The goal of this study was to measure our ability to operate in a congested space environment by estimating the number of detailed conjunction assessments that must be performed per day and the number of collision avoidance maneuvers required to maintain a safe separation between objects. The goal was to determine how number of these events will be impacted if the following is achieved in the future: a system is fielded to actively remove space debris and/or tracking improvements reduce the positional uncertainties associated with each object.

3. METHODOLOGY

In order to make the problem more tractable while remaining relevant we limited the scope of our analysis to look only at the operational stresses, in terms of conjunctions assessments and collision avoidance maneuvers required for Department of Defense and Intelligence Community satellites that traverse through LEO. We focused on LEO because it is heavily utilized and because it has the highest density of debris objects. In modeling the debris population we limited our analysis to debris objects that are large enough to be tracked. This limited our analysis to 44 operational satellites vs. between 13,310 and 17,029 debris objects depending on the time frame.

3.1 MODELING DEBRIS EVOLUTION TO ESTIMATE FUTURE DEBRIS POPULATIONS

To perform the analysis required for this study, an up-to-date orbital debris model with associated predictions of the future debris field was required. The available orbital debris flux models do not include the recent Chinese Fengyun-1C event in January 2007 or the Iridium-33/Cosmos-2251 collision of February 2009. It should be noted that updates to these models are expected in calendar year 2010. Figure 1 shows the historical number of objects in Low Earth Orbit (LEO) along with most severe debris-generating events ("severe" as a measure of the number of objects that were tracked from the event) and shows the necessity of including the recent events in analysis of future missions. The Fengyun-1C and Iridium/Cosmos events significantly changed the LEO environment, together roughly doubling the amount of tracked debris objects in LEO.
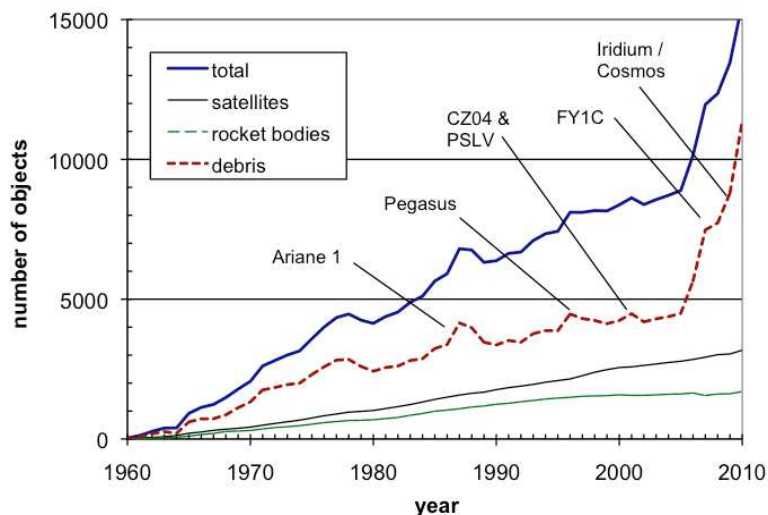

Fig. 1. Number of objects in LEO

Figure 2 depicts the process that was used to generate the predicted debris population at future times[1]. The starting population was assumed to consist of two parts. The first was the public Resident Space Object (RSO) catalog produced by the Joint Space Operations Center (JSpOC), dated June of 2009. This will be referred to as the current population. The second population was a model of the future launch activity. The future launch activity was represented by the last 10 years of historical activity and consisted of a total of approximately 1100 new objects added over each 10-year time span.
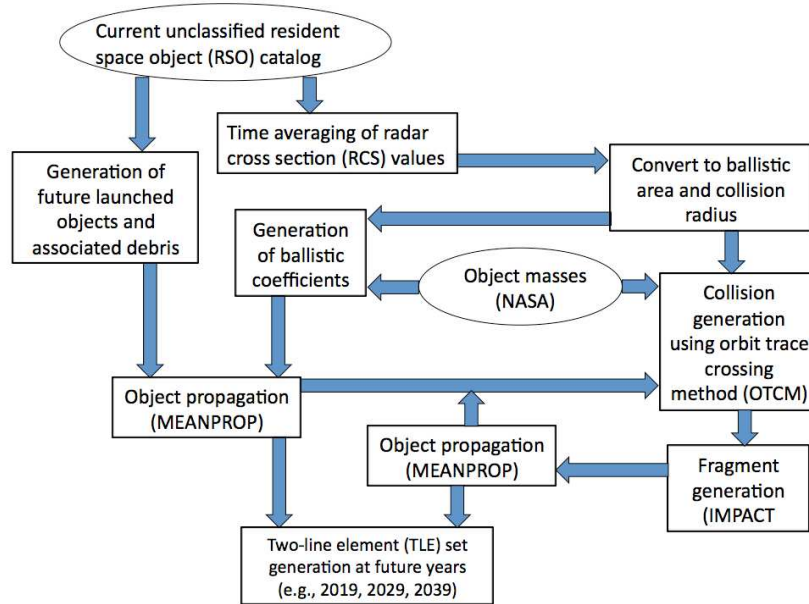
Fig. 2. Schematic diagram of population generation process

The current and future populations were propagated forward in time for 30 years using the mean element propagator MEANPROP (based on a version of Draper Lab's SOAP[2]) and the MSIS-90E atmosphere with mean atmospheric activity to represent drag along with 16x16 EGM gravity field, solar radiation pressure, and Sun and Moon third body effects. To properly capture the relevant perturbing forces on the objects, cross-sectional areas and masses were required. The masses were derived from a database produced by NASA while the areas were computed using radar cross sectional (RCS) values from the RSO catalog. However, past studies have shown that the individual RCS values for the same object can be highly noisy due to altitude, atmosphere, and site dependent calculation techniques, even for spherical objects. To account for this, each object in the catalog had an average RCS computed over all available historical values and then converted to a characteristic length through the NASA Size Estimation Model. The final size was used as the basis for the collision radii with the characteristic lengths scaled to match specific known objects.

Collisions were generated using an orbit trace crossing method (OCTM) where each pair of objects was examined to determine if their orbits crossed (if they didn't, then no collision was possible). When an orbit trace crossing was discovered, the collision probability was computed assuming the in-track positions of the two objects were not known. The collision probability represents the likelihood that the two objects are in the same location at the same time and is thus a small number. A random variate was then drawn from a uniform distribution over the interval [0,1]. A collision was assumed to occur if the random variate was less than the probability of collision. A Monte Carlo simulation of 100 separate cases was generated to simulate a broad range of collision scenarios[1].

The program IMPACT was utilized to determine the resulting debris field from each simulated collision. IMPACT is a semi-empirical explosion and hypervelocity collision model developed by The Aerospace Corporation[3]. IMPACT enforces energy, mass, and momentum conservation. It produces either a statistical representation of the debris field created by the collision or a discrete representation of the debris field that has equivalent statistical properties. For the current analysis to be able to model individual conjunctions and their effect on mission utility, the discrete population averaged over the 100 Monte Carlo cases was utilized.

The process is repeated to account for new debris potentially causing additional collisions and hence creating even more debris (first generation debris, second generation debris, etc.). The advantage of this combination of RCS-based

size estimation, orbit trace crossing method, and IMPACT collision model is that it accounts for correlations in collision parameters including orbital geometry and masses of colliding objects.

The results of this model are shown in Fig. 3 and 4. Fig. 3 shows the average number of predicted objects in LEO as a function of time. The current population shows the expected decrease due to the decay of lower altitude objects while the future launch activity shows growth as more objects are placed into orbit. Since the current population dominates the number of objects, the current population also dominates the collisions with the future collisions showing small influence on the result. Of interest to note is that even with no launches (i.e., the future activity was removed from the simulation), the overall number of objects in LEO will still grow due to the collisions between currently orbiting objects. The growth is not dramatic over the 30-year timescale, but the results indicate the debris population in LEO is self-perpetuating. Fig. 4 shows the altitude variation in the LEO environment at 10-year intervals (year 0 is 2009, the beginning of the modeling effort). As can be seen, the flux generally increases over this time span, but not to a substantial degree. At ~850 km, the density of objects increases by approximately 50% over the next 30 years.
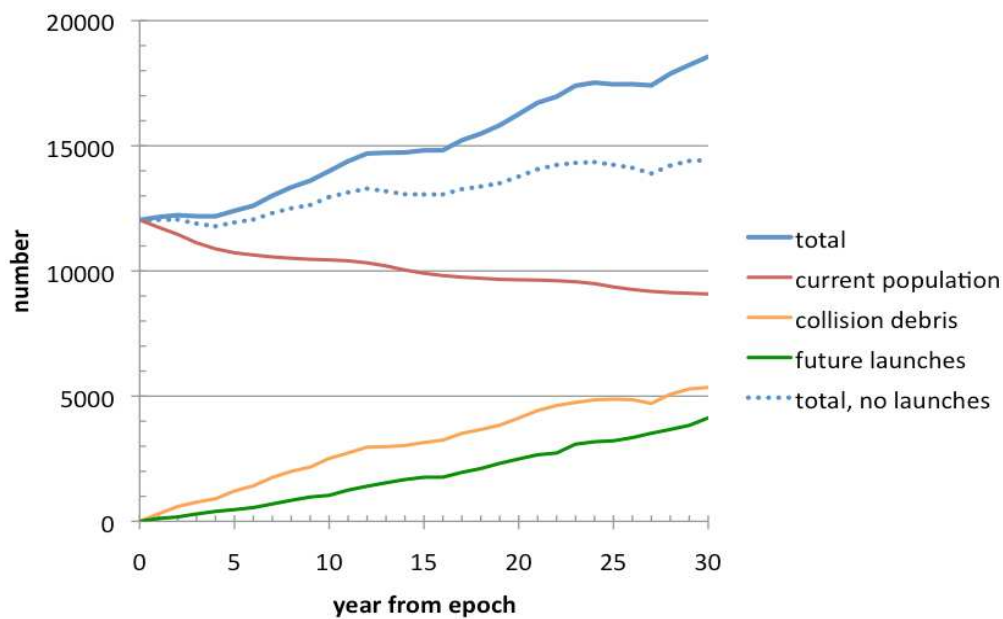

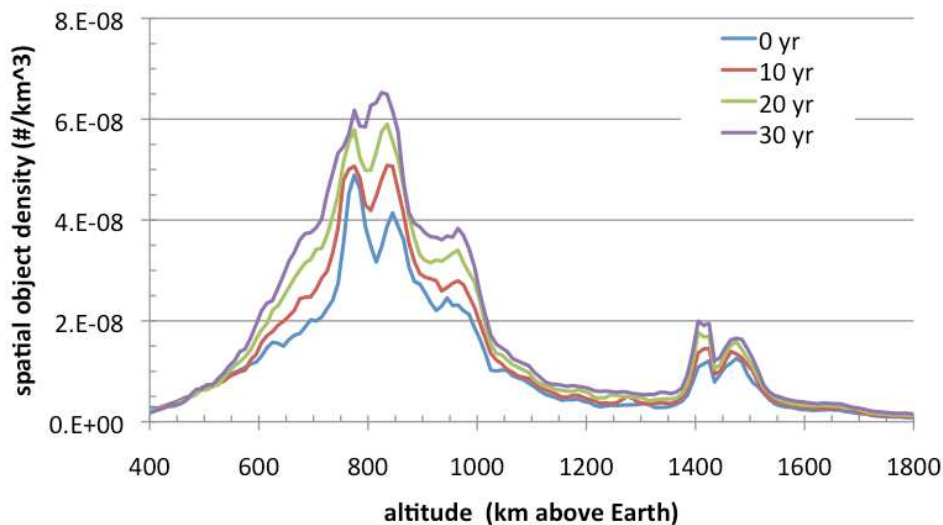
Fig. 3. Predicted number of objects in LEO

Fig. 4: Spatial density for tracked (>10 cm) objects (year 0 = 2009)

3.2   MODELING OF POSITIONAL UNCERTAINTIES

With perfect information regarding the location of these space objects it would be possible to prevent all collisions with maneuverable objects with a negligible expenditure of Delta-V and negligible loading on command and control systems since actual collision events are extremely rare. However our measurements and propagation models are imperfect, as a result when we try to predict a satellite's location days into the future using orbits derived from past observations there are significant positional uncertainties that result. The location predicted at a time in the future cannot be accurately represented by a single point but is more accurately represented as a three dimensional probability density function. The shape of the probability density is actually quite complex but for the purposes of analysis this positional uncertainty region can be roughly approximated by a Gaussian ellipsoid with a long cigar shape with different growth rates in the in-track, cross-track and normal components. The equations describing the mean one sigma positional error estimate growth rates were derived by The Aerospace Corporation team by analyzing updates to the public Resident Space Object catalogue. Whenever a Two Line Element (TLE) set was updated for a non-maneuverable object the distance was calculated from the new location at the new epoch to the location that would have been predicted at that time using the old TLE. The results were used to derive quadratic polynomial equations that describe the one sigma value for positional uncertainty in each component (in-track, cross-track, and normal) based on the time that has elapsed since a track update. It was observed that the uncertainty regions grew at different rates based on the object's altitude so the three separate sets of equations were derived, one for objects below 600km, one for objects between 600km and 700km, and another for objects above 700km. These uncertainty regions were then scaled by 1/3 to approximate Special Perturbations accuracy.

Now that we have a model for the positional uncertainty as a function of time, the next step was to determine reasonable estimates for the amount of time that would have elapsed since an RSO state vector update. By conducting further analysis of updates to the unclassified RSO catalogue the probability distribution for this metric was calculated for LEO payloads and LEO debris. The graph below shows the cumulative probability that the given amount of time has elapsed since the TLE for a LEO object was generated given that the catalogue is current up to the minute. The data show that active payloads are updated more frequently than tracks for debris objects so two different distributions were used to model the delay between state vector updates based on the type of object.
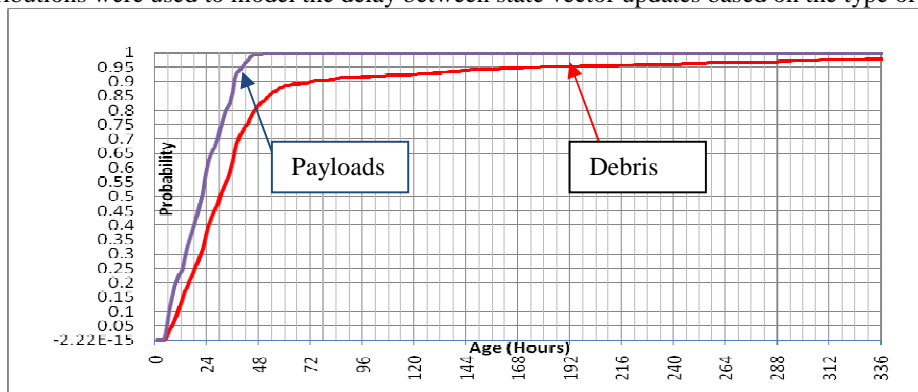

Fig. 5. Cumulative probability of track age for LEO objects in the unclassified SatCat

The calculation of the three dimensional positional uncertainty ellipsoid as a function of the time elapsed since a state vector update for an object is extremely useful when looking at events in the future where the exact sensor and associated covariance's associated with the observations is unknown. We used these uncertainty regions to create a filtered list of high risk conjunctions. The following table shows the estimated probability that the space object is located outside of the positional uncertainty region calculated using the described equations out to 6σ.

σ Defining Ellipsoid	Probability Object is Inside Volume	Expected portion of conjunctions where object is outside uncertainty ellipsoid	Conjunctions/month/sat in 2039 (volumes overlap at < x sigma)
1σ	0.682689492137	~ 1 in 3	~ 1.8 (max 7)
2σ	0.954499736104	~ 1 in 22	~ 7.6 (max 23)
3σ	0.997300203937	~ 1 in 370	~ 18 (max 43)
4σ	0.999936657516	~ 1 in 15,787	~ 33.6 (max 79)
5σ	0.999999426697	~ 1 in 1,744,278	~ 54.4 (max 126)
6σ	0.999999998027	~ 1 in 506,842,372	~ 81.4 (max 184)

Fig. 6. Table showing the impact of using scaled positional uncertainty regions as safety buffers

3.3   DETERMINING EXPECTED CONJUNCTION RATES

To determine the rate of high risk conjunctions we modeled the orbits of 44 selected DoD/IC satellites and the trackable debris objects for each timeframe (2019, 2029, and 2039) were simulated in the System Effectiveness Analysis Simulation (SEAS). SEAS is a Government Off The Shelf (GOTS) maintained by the United States Air Force Space Command's Space and Missile Systems Center. For each Monte Carlo run all objects were propagated for 30 days using Astro Standard Simplified General Perturbations (SGP4) propagator. Whenever an object passed within 800km of our satellites of interest, conjunction assessments were automatically performed. We used several methods to build and compare conjunction lists. The primary and recommended method was to use safety buffers described above based on the estimated positional uncertainties for each object. However we also used the more traditional system developed by NASA of using fixed safety volumes to screen for high risk conjunctions. The table below shows the dimensions of the safety volumes. [4]

Safety Volumes	Radial	In-Track	Cross-Track
Monitor Volume (ellipsoid)	±2 km	±25 km	±25 km
Tasking Volume (box)	±0.5 km	±5 km	±5 km
Watch Volume (sphere)	1 km stand-off radius		

Fig. 7. Safety volume definitions used by NASA for conjunction reporting

The SEAS model calculates whenever any of these safety volumes would be penetrated by a piece of debris. We compared the NASA method of using fixed safety volumes to our proposed method of calculating the predicted positional uncertainty ellipsoids for each object and determining the amount of overlap. We discovered three key benefits favoring the use of dynamically sized safety buffers based on the objects positional uncertainty volume.

1) The positional uncertainty method indentified additional high risk conjunctions that failed to meet the monitor volume, tasking volume and watch volume criteria and would have been accidentally ignored. (see row three in fig. 8 below)
2) A significant reduction in the total number of high risk conjunctions reported is achieved vs. using the NASA monitor volume. Where many close approaches could be determined to be safe based on track accuracies and orbital geometries before reporting. (see row 2 in fig 8 below)
3) Any improvements in our tracking ability that reduce positional uncertainty further reduce the number of high risk conjunctions reported using the positional uncertainty method whereas the conjunction lists generated by the NASA safety volumes would remain just as large.

Average number of occurrences (per month per sat)	Positional Uncertainty Ellipsoid Size					
	6σ	5σ	4σ	3σ	2σ	1σ
Conjunction identified by both Monitor Volume and Positional Uncertainty Regions	~19.1	~15.6	~11.9	~7.6	~3.9	~1.2
Extra "junk" conjunctions reported by monitor volume when positional uncertainty regions do not overlap	~121.2	~124.7	~128.4	~132.7	~136.4	~139.1
Positional Uncertainty Region Overlaps Missed by Monitor Volume	~62.2	~38.8	~21.8	~10.4	~3.7	~0.6

Fig. 8 Table highlighting the difference in the number of conjunctions reported by each method

We have successfully demonstrated that one can rapidly generate a smaller, more accurate list of conjunctions by using this positional uncertainty method. These calculations are automated in the SEAS model and the algorithms are efficient enough to perform many vs. all conjunction analysis at 30+ times realtime on single laptop CPU.

3.4   EXPERIMENT

After calculating the expected number of conjunctions that violate the positional uncertainty regions of all sizes out to 6σ, we conducted the following experiment to see how the number of uncertainty region violations would be reduced if the following improvements are made. The table below describes the experimental parameters.

Experimental Parameter	Values
Number of debris objects actively removed	(0-50 objects)
Percent reduction in RSO state vector position error at time of update	(5%, 10%, 15%, … 95%)
Percent reduction in RSO state vector position error growth rate	(5%, 10%, 15%, … 95%)
Percent reduction in the typical delay between RSO state vector updates	(5%, 10%, 15%, … 95%)

A full factorial sweep of the experimental parameters was conducted in the simulation. The equations describing the positional uncertainty as a function of time were updated for each combination of experimental parameters. Conjunction analysis was performed again to calculate the number of conjunctions that violate the associated smaller positional uncertainty regions. The percent reductions achieved are detailed in section 5.

4. OBSERVATIONS REGARDING CONJUNCTION DISTRIBUTION

One observation that was clearly apparent in all of our results and rather intuitive is that for conjunction events in Low Earth Orbit there is a dense clustering of events at the north and south poles. This is a natural consequence of so many objects being in sunsyncronous orbit, these objects all have high inclinations and similar altitudes thus they end up passing through a small volume of space at the poles such that there is a much higher density of objects in this region. Note the geospatial distribution of conjunction events in fig. 9 and 10 below.
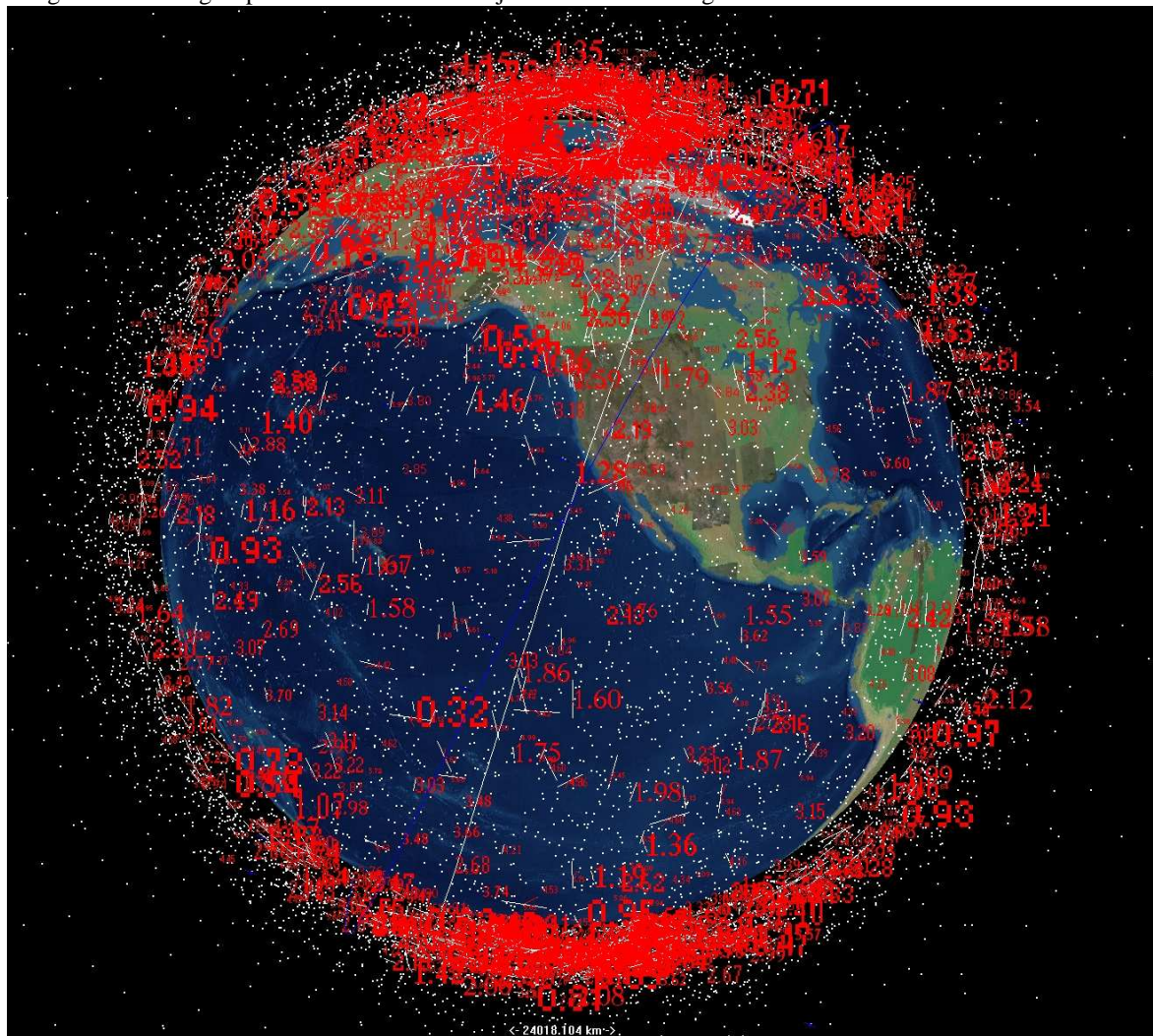

Fig. 9. A screen capture from the SEAS simulation showing the geospatial distribution of a month's worth of conjunctions in the northern hemisphere for 44 LEO satellites vs. the 17,029 >10cm debris objects predicted in 2039. Each white dot represents a debris object (not to scale). The red text indicates the location of a conjunction event, the larger the text the higher risk the conjunction, the numerical value is the number of standard deviations at which the positional uncertainty regions for each object overlap.
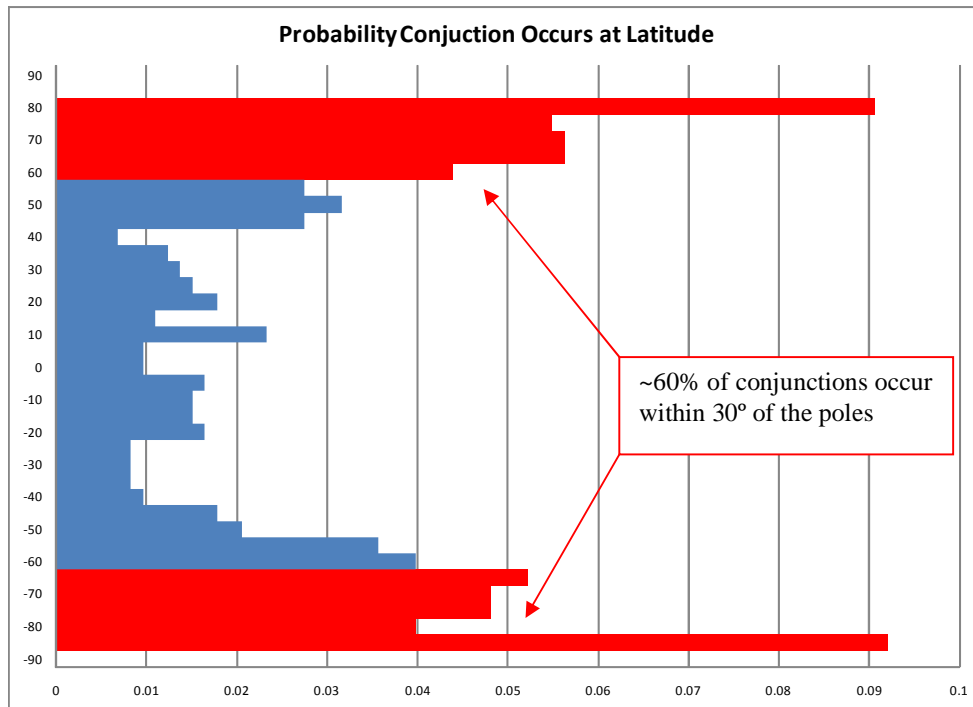
Fig. 10. A graph showing the probability that a conjunction occurs within the 5º latitude band. This specific graph is for 6σ positional uncertainty regions in 2039 but the same trend is evident in all timeframes and all safety volumes

In general the density of conjunction events are correlated with the density of resident space objects. This is also true of the altitude at which conjunctions occur. These data indicate that the non-uniform density of objects in space could potentially be exploited when planning orbits. We recommend that system planners model all proposed orbits and conduct a similarly detailed analysis of conjunctions over the expected life of the satellite to select an orbit that attempts to minimize the number of expected conjunctions while optimizing the satellite access to named areas of interest and ground segment nodes. By being cautious and selecting orbits that traverse less densely populated regions in space one can decrease the number of expected conjunctions and in turn the number of collision avoidance maneuvers required to maintain a safety buffer around the space vehicle. Such planning can reduce the risk of collision and decrease the Delta-V consumed for COLA maneuvers possibly extending the usable life of the satellite.

If a satellite has a high inclination and will traverse the polar regions we further recommend that operators consider the possibility of orienting the satellite and/or its solar panels (pitch and yaw) to reduce the presented surface area in the most probable encounter plane. One should balance power generation needs and slewing responsiveness requirements with the potential reduction in collision probability.

5.   RESULTS

If no improvement is made in regard to our space tracking capabilities then the expected number of conjunctions that will likely require collision avoidance maneuvers to keep a safe separation between objects will become excessive within the next 30 years. The next paragraphs detail how the number of events can be dramatically reduced by making small improvements.

The impact of active debris removal was determined to be negligible for the satellites we examined. We found that very few debris objects turned out to be reliable repeat offenders. Those that were repeat offenders were most often in a chase pattern with the primary object such that the number of high risk conjunctions could be just as effectively reduced by maneuvering the primary object to get the two objects out of sync instead of removing the object from orbit. To highlight this phenomenon I will give an example from a selected of run of the model… out of the 3011 high risk conjunctions identified during the month, the piece of debris responsible for the most conjunctions had only 11 conjunction events. Of those 11 events, 9 were a result of that debris object and the primary satellite being in a chase pattern. Fig. 11 shows the best possible percentage reduction in the number of conjunctions and assumes perfect information regarding which debris objects are the worst offenders so that removal is prioritized.

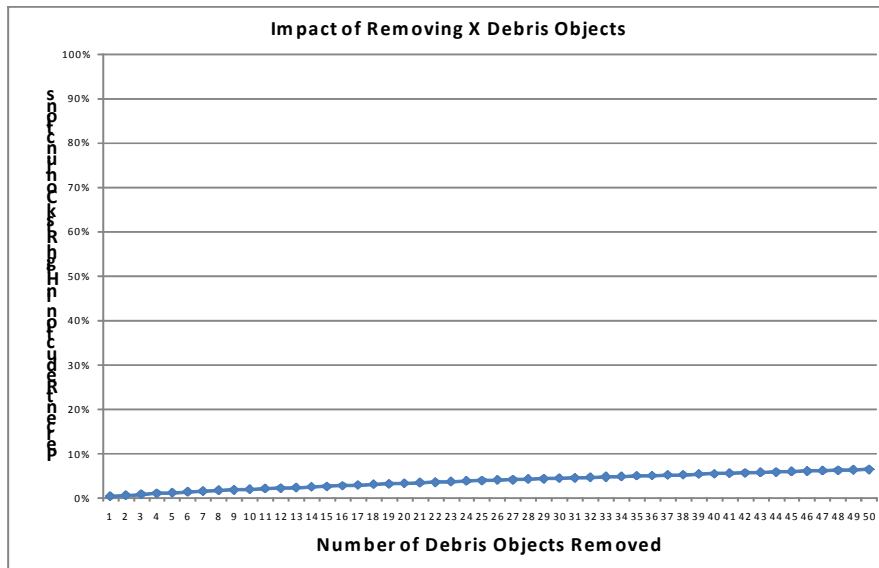**Impact of Removing X Debris Objects**

Fig. 11. Graph showing percent reduction in conjunctions achieved as a result of debris removal

The impact of debris removal is far overshadowed by the factors below related to the quality of information regarding the objects location. It was determined that making even small improvements in our space tracking ability has a far greater impact on reducing the number of conjunctions.

Percent Reduction in RSO State Vector Position Error At Time of Update
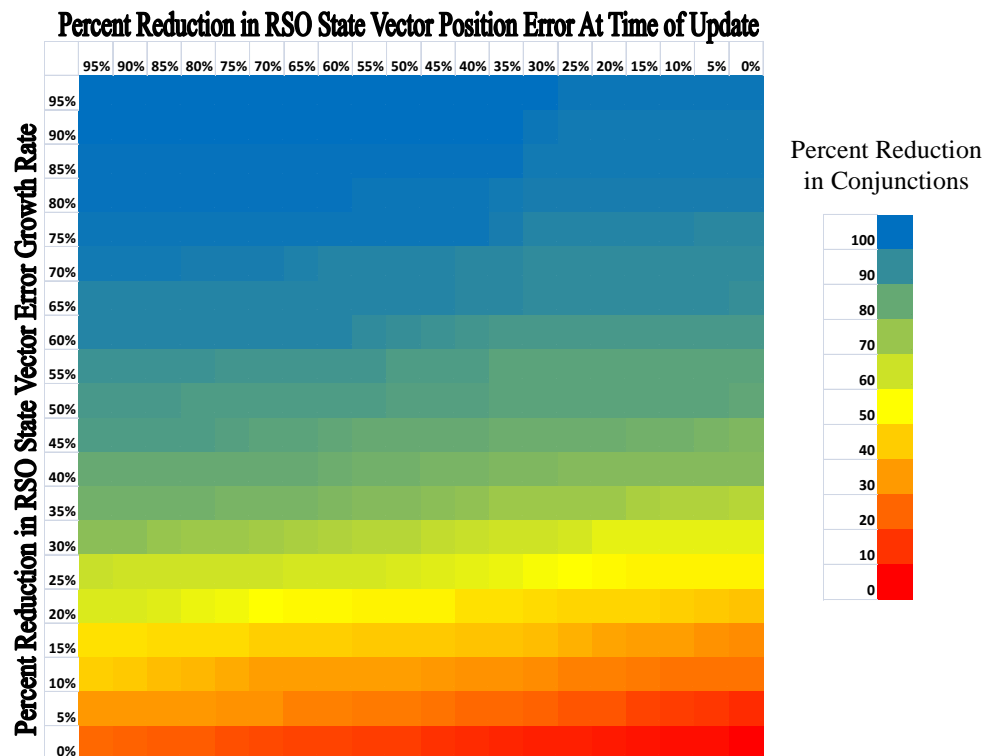
Fig. 12. Matrix showing the percent reductions in conjunctions achievable by reducing state vector errors

Fig. 12 shows that a percent reduction in the position error growth rate is worth more than a percent reduction in the starting position error at the time of a state vector update. Error growth rate is clearly the dominate factor between these two. Error growth also dominates debris removal as just a 10 percent reduction in the position error growth rate is approximately three times more valuable then removing 50 debris objects.

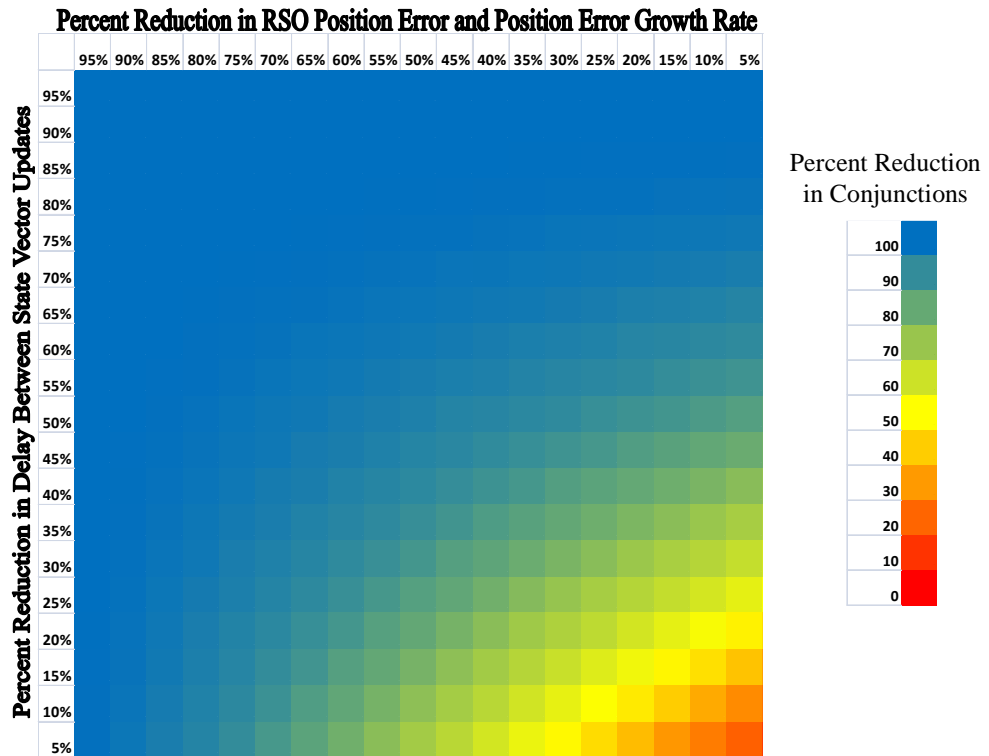**Percent Reduction in RSO Position Error and Position Error Growth Rate**

Fig. 13. Matrix showing the percent reductions in conjunctions achievable by reducing the delay between track updates and state vector errors and error growth rate

6. CONCLUSIONS

For the satellites we examined, our results highlight the following. Even though a significant increase in the debris population is projected there will be little benefit in developing a system to actively deorbit debris objects. In fact our data indicate that the largest reduction in conjunctions and collision avoidance maneuvers will result simply from increasing the rate with which debris state vectors are updated. Further reductions in the expected number of conjunctions can be achieved by improving the quality of our observations and force models to reduce the position error growth rate when predicting where the object will be in the future. Reducing both delay and position error growth has a synergistic effect. Using the conjunction list to cue SSN assets to provide high quality just in time state vector updates for debris objects prior to conjunction with a primary object may be enough to avoid the need for COLA maneuvers for a significant proportion of predicted conjunctions. Other gains may be possible by adding additional SSN assets and/or optimizing how SSN assets are scheduled. It appears that the key to success in future debris environment is reducing the positional uncertainty for debris which is currently significantly greater that the positional uncertainty associated with payloads.

7. REFERENCES

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