An Investigation into Transecting Satellites in Future Space Traffic Management Scenarios

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ABSTRACT

The number of satellites expected to populate the near-Earth space environment is set to dramatically increase in the coming decade as new large constellations are approved and deployed. Current strategies for deploying new batches of these satellites often involve launching into an initial orbit, and then performing apogee raising maneuvers to reach a target altitude. Similarly, end-of-life planning for these constellation satellites can consist of de-orbit burns that lower perigee to permit disposal via re-entry. Both the raising and de-orbiting maneuvers can result in the individual satellites traveling in transecting orbits that have the potential to cross other spacecraft trajectories. While individual large constellations may be able to coexist in separate altitude and inclination bands, having thousands of satellites moving between these bands as new satellites are added and old satellites are removed could pose additional collision risks. Similar concerns have been raised regarding the impact that large numbers of university-class CubeSats might have in terms of their overall collision risk, especially as these satellites typically do not have propulsion systems for active maneuvering.

To assess the impact that transecting satellites might have on future space traffic management strategies, this study explored a variety of realistic future scenarios using a high-fidelity simulation tool. The model can simulate the orbit of tens of thousands of resident space objects (RSOs) simultaneously, to include active satellites, debris, rocket bodies, or even future hypothetical satellite constellations, using a realistic force model that incorporates non-spherical gravity, atmospheric drag, and solar radiation pressure, as well as station-keeping. The simulation can be customized to accommodate different methods of calculating the probability of collision, as well as the process for determining probability ellipsoids and screening volumes. This makes it possible to replicate, and compare, different processes used by different spacecraft operators and space situational awareness (SSA) providers. As the model is run forward in time, each conjunction event is recorded, allowing for the analysis of statistics and meta-data related to these events, providing insight into the nature and frequency of potential collisions, such as whether are they active or passive objects, what size are the two objects, and who owns the objects (if known). This information makes it possible to characterize how changes to the status quo affect the number and type of conjunctions that occur, as well as the distributional effects on various types of satellite operators.

To assess the general risks that transecting satellites might pose for hypothetical future space object environments, approximately 60,000 new large constellation satellites were considered, in addition to the existing catalog of approximately 7800 known resident space objects (RSOs), over a simulation period of one year. The results indicate that the future space environment will introduce a non-linear increase in conjunction events as the number of RSOs also increase. This will require adjustments to spacecraft fuel budgets in order to conduct the avoidance maneuvers necessary to minimize collision risk, both for existing and new satellites. This increase is due in large part to the higher density of RSOs and the overlap between some constellation orbits. Current catalog objects were shown to require three times more ΔV for collision avoidance (CA) maneuvers in the simulated future environment, and some constellation spacecraft were estimated to devote the majority of their annual ΔV to CA. The impact of small satellites was found to be proportional for the current space environment, and actually decreased in terms of percentage for the future scenario, suggesting that small satellites do not pose an outsized collision risk. Lastly, transecting satellites were found to contribute thousands of additional conjunctions outside of their operational orbit, and may require up to an additional 5% in CA maneuver fuel allocation.

1. INTRODUCTION

The coming decade is expected to see a substantial increase in the number of Resident Space Objects (RSO's) as various commercial and government entities realize various large satellite constellations across a range of applications spanning from remote sensing to communications. A recent survey of new constellations likely to be deployed in the near future suggests a conservative estimate of approximately 20+ new systems that would add a total of 64,000 new RSOs to the current catalog of tracked objects [1]. While these new systems have the potential to transform the volume, quality, and accessibility of information to a global user community, the rapid growth in the number of RSO's could represent a significant hazard to near-Earth space operations if not properly coordinated.

The challenges of operating in this environment are heightened by the fact that some large constellation operators have begun using a staging approach when building or replenishing their constellations. Specifically, newly launched satellites are placed into an initial orbit and then raised into their target orbit through a series of apogee raising maneuvers that result in transecting orbits that span many hundreds of kilometers in altitude over many weeks. Deorbit burns follow a similar approach. This strategy does promote safety by allowing failures of newly launched satellites to be managed at an altitude that ensures a rapid deorbit, as opposed to having the failure take place in the higher target orbit. That said, the satellites traveling in these transecting orbits that have the potential to cross other spacecraft trajectories, posing collision risks outside their primary operating orbit. One of the objectives of this study is to characterize the risks posed by these types of maneuvers, particularly in a future space environment that consists of multiple large constellations.

Simulation is the optimal choice to explore such large and complex scenarios, since the projected number of future RSOs far exceeds what can be extrapolated from data-mining historical conjunction data. To enable such an analysis, we have developed a software tool [2] that utilizes high-performance computing platforms to handle the large volume of RSOs involved, and accurately models both natural (e.g. gravity, atmosphere) and operational (e.g. orbit raising/de-orbit, station-keeping) forces for simulation runs lasting months to years. During each run, the tool continuously gathers information on conjunctions, including meta-data of the RSOs involved, so that aggregate statistics and behaviors can be examined.

Most importantly, the tool goes beyond just propagating orbits and reporting conjunctions – which is what most STM website and software tools provide -- and has implemented run-time maneuver and avoidance capabilities so that various rules or guidelines can be explored in a dynamic and evolving environment over long periods of time [3]. Different methodologies for covariance and probability of collision (Pc), even different orbit propagators, can also be activated to examine their impact on the results. The intent is that the software tool developed provides the capability to explore a wide range of environments and maneuver strategies to ideally anticipate and provide solutions to the challenges that a dense future space environment will inevitably present.

The first phase of this study was to simulate a realistic future space environment and examine the baseline collision risk in this situation. Initial experiments involved the evaluation of conjunction histories for a select collection of projected large constellations that were assumed to have already been deployed and in their final operational configuration. This baseline scenario established how frequently and where conjunctions occurred, in particular interconstellation events, under the assumption that intra-constellation avoidance maneuvering is managed by the individual operators. Additional data was gathered on the collision risk with specific satellite groups, such as small satellites, which were defined as those satellites under 180 kg. Small satellites were of interest as they often do not have active propulsion systems capable of maneuvering and, as a result, may have an impact on maneuver guidelines or recommendations for orbit regimes that have minimal impact on other RSOs. Subsequent simulations focused on the specific aspect of long-term constellation maintenance where aging satellites are decommissioned, deorbited, and replaced with new satellites, resulting in regular transections of other orbits. Characterizing the risk associated with these maneuvers can help to inform constellation operators' future planning as well as potential guidelines for improved space traffic coordination for these future scenarios.

The results show that there is expected to be a significant increase in conjunction events with the new constellations, that scale non-linearly with the number of objects. This was linked to a corresponding change in spacecraft fuel budgets to support the additional collision avoidance maneuvers that would be needed. In some cases, the allocation for collision avoidance comprised a majority of the annual operating fuel budget. Small satellites were not shown to be a significant contributor to overall collision risk. Similarly, transecting satellites were not a major conjunction

source, but did generate tens of thousands of estimated new events that would need to be factored into spacecraft fuel budgets and operations.

2. METHODOLOGY

2.1. Selection of constellation satellites

In order to evaluate the impact of transecting satellites, an initial set of constellations was first selected. While any choices made are considered somewhat speculative, the goal was to identify a set of likely constellations and create a representative future space environment. A parallel study was performed [1] in conjunction with the simulation development to look into publicly available resources such as Federal Communications Commission (FCC) filings, company news releases, journal papers, preliminary launches, and other data to compile a select list of constellations to include in the simulation runs. The constellations listed in Table 1 show those constellations that were believed to have a strong likelihood of being realized.

Constellation	Company	Country	# Satellites
Astra	Astra	USA	13620
GuoWang (GW-2/GW-A59)	China Telecom	China	12992
Kuiper	Amazon	USA	3236
OneWeb	OneWeb	UK	648
Starlink (Gen2)	SpaceX	USA	29988
Total	60484		

Table 1. Predicted satellite constellations evaluated in the simulations

From the same literature search (FCC filings, etc.), an associated list of orbit parameters for each of the constellations was also developed, as well as a set of satellite parameters (mass, size, etc.). Not all constellations had clearly defined plans and spacecraft designs in the public domain, so in some instances assumptions needed to be made in order to have enough information to incorporate them in the simulation. For example, the assumed mass for all Guo Wang satellites was 1738 kg, 300 kg for Astra, and 260kg for Starlink (2nd Generation), and the hard-body radius was set to 4.43 meters for all satellites for which specific size information was not known. Figure 1 provides a visualization of the various constellations, and Table 2 provides a summary of the assumed orbital parameters for each constellation. Again, the intent was to develop a representative environment that mirrors reality as closely as possible, but recognizing that the actual realization of these constellations listed in Table 1 does emphasize that active plans are being made by a number of entities in both the public and private sectors across the globe that will result in many tens of thousands of new satellites being placed in orbit within the near future.



Figure 1. Visualization of a select number of constellations examined in the simulations

Constellation Configuration	# Satellites	Altitude (km)	Inclination (deg)	Planes
Starlink Gen2	5,280	340	53	48
Starlink Gen2	5,280	345	46	48
Starlink Gen2	5,280	350	38	48
Starlink Gen2	3,600	360	96.9	30
Starlink Gen2	3,360	525	53	28
Starlink Gen2	3,360	530	43	23
Starlink Gen2	3,360	535	33	28
Starlink Gen2	144	604	148	12
Starlink Gen2	324	614	115.7	18
Kuiper Shell 1	1,156	630	51.9	34
Kuiper Shell 2	1,296	610	42	36
Kuiper Shell 3	784	590	33	28
Astra Phase 1.0	40	700	0	1
Astra Phase 2.0	504	690	98	14
Astra Phase 2.0	1,792	700	55	56
Astra Phase 3.0	2,240	380	97	20
Astra Phase 3.0	4,896	390	30	51
Astra Phase 3.0	4,148	400	55	61
OneWeb	648	1,200	86.4	12
GW-A59	480	590	85	16
GW-A59	2,000	600	50	40
GW-A59	3,600	508	55	60
GW-2	1,728	1145	30	48
GW-2	1,728	1145	40	48
GW-2	1,728	1145	50	48
GW-2	1,728	1145	60	48

Table 2. Orbit parameters of the five major modelled constellations

2.2. Simulation Environment

The simulation environment used is explained in more detail in [2][4], to include validation comparisons against realdata, so the reader is encouraged to reference these earlier works for a more complete description of the methodologies used. A summary of the simulation workflow is provided here for convenience.

Each simulation begins with an initialization of the environment, which is typically done by inputting a collection of two-line element (TLE) sets that describe the various RSOs that will be considered for that particular run. The tool can currently handle upwards of 250,000 objects using a relatively modest compute platform (e.g., a single node with 15 GB of total memory and 20+ compute cores), with wall-clock run times for a one-year simulation timeframe typically under one day. This allows the submission of numerous simultaneous runs across multiple nodes to quickly explore variations in the simulation parameters. For this study, the total number of constellation RSOs totaled 60484, as shown in Table 1, which was added to the 7792 existing known set of active catalog objects obtained from SpaceTrack^{*} on February 4th, 2023, for a total count of 67626 RSOs (accounting for some duplicates between the

^{*} www.space-track.org

current catalog and constellation count). It is important to note that these objects are restricted to active satellites only, and debris objects were not considered. Additional simulation settings include the propagator options, the choice of Pc calculation, conjunction parameters (Pc levels, screening volume, hard-body radius assumptions, warning/maneuver lead times, etc.), simulation duration, and maneuver guidelines. While in reality there is some variation in the approach to identifying conjunctions among different entities, to reduce the overall number of runs, this study used the following for all simulations:

- Pc calculations using Chan's method [5], using a 25 km screening volume
- Conjunction warnings at Pc > 1e-5, computed at 72 hours prior to time of closest approach (TCA)
- Avoidance maneuvers, if enabled, would occur at 48 hours prior to TCA, using a standard phasing maneuver.
- Position covariance for each RSO is constant throughout the simulation, and is derived from either real TLE data or, if no TLE history is available, a default set of covariance values were used.
- Simulation time frame is one year.
- Orbit propagation includes non-spherical gravity, solar radiation pressure, third-body forces, and atmospheric drag as implemented in SGP4 [6].

After initialization, at two-minute increments, all objects are propagated forward and checks for conjunctions are performed for the prescribed lead time (e.g., 72 hours). This step interval is another simulation variable, but two minutes was determined through experimentation to be a reasonable balance between computational efficiency and fidelity. If a conjunction is found with a Pc above a prescribed threshold (1e-5 for this study), then the event details are logged, to include the various attributes of the objects involved. If one or more of the RSOs have maneuvering capabilities, then an avoidance maneuver is performed 48 hours prior to TCA if the Pc is above 1e-5. Checks are performed to ensure the phasing maneuver doesn't introduce additional conjunctions, with adjustments to the maneuver made if that's the case. The decision on how and which RSO maneuvers is controlled through various additional checks, e.g., using a priority ranking or other attribute (country, operator, etc.). For this study, the maneuver burden was set to be split equally if a conjunction involved two maneuverable satellites. The simulation can accommodate different forms of maneuvers, but for the purposes of this study, it was configured to perform a simple phasing maneuver lasting 48 hours, i.e., a two-impulse along-track thruster firing sequence. A full maneuver includes the initial avoidance step, and then a similar process to return the satellite to its original orbit location. The cost in units of velocity change (i.e., ΔV) are recorded to assess the impact in terms of required spacecraft fuel for the various scenarios.

The simulations are intended to run over time frames of months to years to be able to generate a sufficient number of actionable events (i.e., Pc > 1e-5). Such long integration times can lead to significant changes in the RSO orbits due to the accumulation of non-conservative forces such as atmospheric drag. This can even be enough to fully deorbit or place some constellation satellites well beyond their target altitudes. To more accurately reflect the true operational mode of a large constellation, additional functionality was incorporated into the simulations to perform basic station keeping maneuvers. In short, each constellation satellite is assigned a specific altitude and true anomaly bounding box within its initial orbit plane. If that satellite drifts to the edge of the bounding box. At the moment, station keeping and avoidance maneuvering are treated as separate events, but it is recognized that operators would want to combine these maneuvers for efficiency, and is a feature that will be added to the simulation tool in future revisions.

2.3. Modeling transecting satellites

The primary objective of this study is to assess the impact of transecting satellites. In order to do this, an analysis into how current large constellations deploy and deorbit their satellites was first performed to gain insight into how to best model and emulate this approach in the simulation. The Starlink and OneWeb constellations were two constellations studied, since they represent two of the larger constellations currently on orbit, and the satellites for both of these systems have active propulsions systems. In addition, both constellations have been in operation long enough for trends in deployment and deorbit to be observed in publicly available TLE data. Figure 2 shows one example of a time series of altitude for a group of first-generation Starlink satellites. The figure shows the full life cycle of many of the satellites, and highlights the deployment strategy of launching satellites into a low initial orbit before raising them to their target orbit (closeup shown in Figure 3a). This orbit raising maneuver typically lasts several weeks,

using low-thrust propulsion, which enables the satellite to maintain its near-circular eccentricity while increasing its semi-major axis (altitude). A similar approach can be seen in the de-orbit process as well, with satellites moving from the target orbit to a lower orbit in approximately the same 3-4 week timeframe before naturally decaying into re-entry. It is interesting to note that not all of the Starlink satellites in Figure 2 were actively deorbited, and some look to have naturally decayed directly from their target orbit. The assumption here is that there is a certain (small) percentage of satellites that fail on orbit and will only de-orbit through a longer natural free-fall re-entry process.



Figure 2. Observed ascent and de-orbiting of 58 Starlink Gen-1 satellites from public TLE datasets

To date, only a handful of OneWeb satellites have failed, so data-mining historical TLE data does not yield a general deorbit procedure for this constellation. The raising process is easier to observe, and an example of 29 OneWeb satellites raising is shown in Figure 3b. Starting at approximately 450 kilometers in altitude, this launch group raises to 900 kilometers over the span of just over two months. This is the first of several staging orbits including one at 1,150 kilometers and a variety within 50 kilometers below the destination altitude. The purpose for these is typically to leverage gravitational perturbations for orbit plane phasing, and staging just below the destination allows a fine-tuned placement among other satellites in a particular plane. The entirety of the process takes approximately three months for OneWeb. Starlink follows a similar pattern, but achieves a destination orbit in less than a month. For constellations that have not yet been deployed, the raising speed must be assumed.

To model this process for the proposed constellations in Table 1, it was assumed that the general build-out approach of new large constellations would follow the same pattern of launching first into a lower check-out orbit before conducting orbit raising to the target orbit. A standard orbit raising period of 30 days was assumed, and the orbit raising maneuvers were performed as a series of small, impulsive thrusts to keep the eccentricity near-zero. Figure 4 shows the modeled orbit raising maneuver for a simulated Starlink and OneWeb satellite, showing their similarity to the observed trajectory shown in Figure 3.



Figure 3. Observed orbit raising for a set of a) Starlink and b) OneWeb satellites based on TLE histories



Figure 4. Modeled orbit raising for a representative a) Starlink and b) OneWeb satellite

The deorbit process is essentially the reverse of the orbit raising maneuver, with the exception that approximately 3% of the satellites are randomly selected to be unable to actively deorbit and to naturally decay from their target orbit.

The real-data analysis of current large constellations showed that individual Low-Earth Orbiting (LEO) satellite members are often retired after a relatively short service lifetime of just a few years (see, for example, Figure 2). Assuming an operator has a maximum rate for building and launching constellations of 1000 satellites per year, for example, it would take 10 years to build out a full constellation of 10,000 satellites, at which point the initial batch of satellites may be ready for retirement. In this scenario, even if the satellites had a longer lifetime of 10 years, the operator would still plan for the deorbit and replacement of 1000 satellites annually to maintain their system. While this is likely a simplification of the actual maintenance schedule of a large constellation, it is sufficient to explore what the impact of the transecting satellites would have on the other catalog objects. It can also provide insight into the level of disruption that might occur as operators rapidly build-up, or fully de-orbit, entire constellations.

Since the timeline for the deployment of the various future constellations is uncertain, this study assumes that all constellations have already been placed in their operational orbits and are at their full designed capacity. Then, an annual replacement and deorbit rate of 10% of all constellation satellites is assumed, with weekly batches of satellites randomly chosen and placed into transecting orbits. For the 60484 new constellation satellite being simulations, this means that approximately 6000 satellites are deployed and raised each year, and 6000 satellites are being deorbited, for a total of 12000 total transecting satellites. This is more than the number of active satellites in the current catalog (7792).

3. RESULTS

3.1. Baseline scenario

Using the simulation settings described in the prior section, a baseline scenario was first established in which each of the new projected constellations were assumed to be operating at their full capacity and in their designated orbits, together with the current catalog of RSOs. The baseline did not include any satellite replacements, so no transecting satellites are involved. The goal for this initial case was to examine the degree to which the constellations in their final form might interfere with each other or other catalog objects. Table 3 provides a high-level summary of the outcome of the baseline simulation. The results with and without the inclusion of intra-constellation events are reported in this table to highlight the volume of events that occur within the constellations. Note that annual values for the intra-constellation events for the baseline case were projected from a shorter one-month simulation (the same holds for the shaded cells in Table 4). Only events with Pc > 1e-5 are considered.

	Current Catalog		Baseline	Scenario
	Excl. Intra Incl. Intra		Excl. Intra	Incl. Intra
				(projected)
RSOs	7792	7792	67626	67626
Pc 1E-2 Events	3	3	11	154
Pc 1E-3 Events	46	42	188	2776
Pc 1E-4 Events	984	1087	13305	152459
Pc 1E-5 Events	10655	31753	317336	1283138
Total event with $Pc > 1E-5$	11688	32884	330840	1438527

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Table 4	Nummary	of the	baseline	scenario	events
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When excluding intra-constellation events, since it is assumed that operators can deconflict collisions with their own satellites, the results indicate that a factor 8.6 increase in total RSOs creates a factor 13.5 increase in interconstellation/catalog events at the 1e-4 Pc level, and a factor 29.8 increase in events at the 1e-5 Pc level. These numbers suggest that the change in conjunctions is not linearly related to an increase in objects. Figure 5 shows the distribution of events for the baseline case over the one-year timeframe. The cadence of events stays mostly steady throughout the simulation, but a spike in events for approximately one month is also observed, suggesting that there may be periods of higher activity.



Figure 5. Time history of simulated conjunction events for the baseline case

Table 4 summarizes the degree to which the different constellations were involved in the conjunctions event, as well as conjunctions with general catalog objects. Unless otherwise specific, conjunctions events are those with a Pc > 1e-5. One notable observation from the baseline scenario is that 309491 events of the 330840 total events involved either a Starlink or GuoWang satellites, or 93.5%. In general, the lower altitude constellations have higher conjunction rates because the satellite density is significantly higher. Three of the five constellations are estimated to perform many hundreds of thousands of CA maneuvers annually, to include both intra-constellations events.

	Astra	GuoWang	Kuiper	OneWeb	Starlink	Catalog
Astra	265932	3607	900	336	31229	12364
GuoWang	3607	96360	16769	1409	103142	30285
Kuiper	900	16769	25611	964	16675	5222
OneWeb	336	1409	964	401	2340	547
Starlink	31229	103142	16675	2340	719121	104035
Catalog	12364	30285	5222	547	104035	1016
Total	314368	251572	66141	5997	976505	153469

Table 4. Summary of conjunction type for the baseline scenario

3.2. Small satellites

One aspect of interest for the simulations was the potential impact that small satellites (to include CubeSats) might have on the overall collision risk in a more crowded space environment. To assess this, event statistics on satellites with mass below 180 kg were gathered, summarized in Table 5. Note that CubeSats were considered as a separate group, and were classified as satellites with a mass < 24kg. Intra-constellation events are not included in the table, since only OneWeb events would have been involved, which were relatively small (401 in total, as seen in Table 4).

Table 5.	Summary	of conj	unction	events	involving	Small	Satellites
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	Current	Baseline
	Catalog	Scenario
Number of Small Satellites (24-180kg)	756	756
Number of Cubesats (0-24 kg)	1078	1078
Events Involving Small Satellites (24-180 kg)	4375	18189
Events Involving CubeSats (0-24 kg)	3058	12718

Of the 330840 total conjunctions estimated from the baseline case, a total of 30907 involved small satellites, or 9.3%. The 1834 small-/CubeSats are approximately 2.7% of the total 67626 total objects simulated (noting that, at 148 kg, OneWeb satellites are included in the set of small satellites). The number of conjunctions involving small satellites increased by a factor of 4 when comparing the events from the current catalog and baseline scenario, which is much less than the increase in total conjunctions seen in Table 3, which showed an overall increase in conjunctions by a factor of 28.3 for Pc > 1e-5.

As an additional experiment, a hypothetical scenario was explored in which the mass and HBR for all constellations was set to that of a CubeSat, i.e., 24 kg and 0.2 m, respectively. The goal was to explore the influence of spacecraft volume on the total conjunction count. The results of this simulation showed that the total number of 1e-5 events decreased to 128958, which is 39% that of the 330840 from the baseline scenario.

3.3. Transecting satellite scenarios

With the baseline case established, a separate series of simulations were performed that focused specifically on the transecting satellites. Again, this assumed that 10% of the total number of satellites for each constellation were deorbited and replaced annually, chosen randomly, with raising and deorbiting groups initiated in weekly batches. For the earlier example with a constellation with 10,000 satellites, that would mean 1000 satellites were randomly selected to deorbit and be replaced over the course of the year, in weekly batches of approximately 38 satellites (19

deorbits, and 19 replacements). For this particular simulation, 60484 total constellations satellites were used, so with a monthly orbit raise/deorbit assumption, this meant that on average 232 satellites were actively transecting at any one time.

Additional simulations runs were made to evaluate the extra maneuvering that might be required from these transecting satellites. Table 6 provides a summary of the results, with only conjunctions reported at Pc > 1e-5 levels for intersatellite conjunctions (ignoring intra-constellation events), and only during the orbit raising/deorbit phase. In addition, this analysis was only performed using a 3-month simulation, so both the 3-month values and a projected one-year rate are shown in the table (multiplying the 3-months values by four).

	3-month	1-yr (projected)
Number of transecting RSOs	4082	16328
Pc 1E-2 Events	0	0
Pc 1E-3 Events	0	0
Pc 1E-4 Events	59	236
Pc 1E-5 Events	1849	7396
Total event with $Pc > 1E-5$	1908	7632

Table 6. Summary of the transecting scenario events

There were a total of 4082 individual transecting RSOs during the three-month simulation run. While the total number of events were expected to be much less than the baseline scenario due purely to the lower number of RSOs involved (4082 vs. 67626), the 1908 events do highlight that there is still a significant number of conjunctions that occur during the raising and deorbiting phases. The projected annual events of 7632 is approximately 2.3% of the total events (330840) for the baseline case, but in terms of pure volume, is ~65% of the total number of events observed from the current catalog (11688) shown in Table 3. It also suggests that operators will need to allocate an additional ΔV allocation for avoidance maneuvers during this phase of the mission, beyond just the amount required for the actual raise/deorbit maneuver, which is discussed next.

3.4. ΔV requirements

To explore the ΔV requirements that both the baseline and transecting satellites would need to meet in order to operate with minimal collision risk, aggregate statistics were gathered on the various maneuvers throughout the simulation duration. The results are summarized in Table 7, and assumes that the maneuver burden is shared equally between active satellites, and that all conjunction warnings are acted upon by both parties with full compliance. The values in Table 7 represent the additional ΔV that each constellation satellite would need to budget, on average, to conduct the various avoidance maneuvers during nominal operations (baseline), and transecting phases. These values are compared against the ΔV required for intra-constellation maneuvers, and station-keeping maneuvers. Note that the column showing the transecting average values were computed from only those satellites that experienced a conjunction during orbit raise/deorbit; however, since the operator does not know in advance if such a conjunction would occur, this would need to be incorporated into the spacecraft's ΔV budget. In addition, the station-keeping and raising/deorbiting values were generated from a weighted average based on the number of satellites in each constellation's orbit planes. One observation from the results is that the CA ΔV budget for general catalog objects increase from 5.36 m/s to 16.93 m/s annually, representing a factor three increase in required maneuver ΔV for existing satellites.

	Current Catalog		Baseline					
Constellation	Intra/Inter- satellite	Inter- satellite	Intra- satellite	Station Keeping	Transecting Average	Total		
Astra	-	6.794	157.112	485.777	1.988	651.67		
GuoWang	-	45.318	31.755	7.727	4.893	89.69		
OneWeb	17.285	13.092	8.113	6.445	1.848	29.50		
Kuiper	-	25.602	23.280	16.642	1.778	67.30		
Starlink	17.452	15.139	27.330	995.936	2.423	1040.83		
Catalog	5.3631	16.933						

Table 7. Summary of Estimated ΔV Budget, in units of m/s



Figure 6. Fractional breakdown of ΔV budget by constellation for the baseline case

Figure 6 shows the fractional breakdown of ΔV required for nominal operations for each constellation's satellites (i.e., excluding the ΔV required for the one-time orbit raising/deorbit maneuvers). The amount spent on each category (inter-satellite CA, intra-satellite CA, etc.) varies for each group, with much of the allocation determined by the altitude of the constellation. For example, the station-keeping budgets for Starlink and Astra are noticeably larger than for the other constellations, due largely to the differences in altitude. The figure does show that for some constellations, the percentage of the annual ΔV budget devoted to CA (i.e., intra-, inter-constellation maneuvers) ranges from 25-85% for Astra, GuoWang, OneWeb and Kuiper, with just 4% for Starlink (due to the large ΔV required for station keeping). For GuoWang, OneWeb and Kuiper, the ΔV needed only for CA during transects was approximately 5%. The average annual CA ΔV allowance for all constellations and existing catalog objects was 62 m/s. Compared to the 13 m/s annual average estimated from objects in the current catalog, this represents a near factor 5 increase in CA ΔV allocation. Overall, these values show that a significant additional ΔV allowance will need to be incorporated into future spacecraft designs.

4. CONCLUSION

This study presents the results of a set of detailed simulations into a potential future space environment that hosts tens of thousands of new satellites from five major planned large constellations. The simulations attempted to reproduce a realistic operating environment, and included full force modeling, station-keeping, orbit raising and deorbiting maneuvers. The intent was to explore the degree to which the increase in resident space objects (RSOs) changed the predicted number of actionable conjunction warnings, defined here as those conjunctions with a probability of collision (Pc) greater than 1e-5. In addition, the investigation into transecting satellites was also performed. Transecting satellites are constellation satellites that are in the process of moving into their target orbit from an initial lower insertion orbit, as well as those satellites who have reached their end-of-life and are being actively deorbited. Simulations spanning one year were performed, with data on each conjunction event logged, to include the fuel cost in terms of ΔV required to conduct an avoidance maneuver. The current design for five major planned constellations was estimated to add 60484 new satellites to the existing catalog of 7792 objects, for a total of 67626 total active objects simulated.

The results of the simulations showed that these new constellation satellites increase the number of conjunction events with Pc > 1e-5 by a factor of 28.3, and suggest a non-linear relation between events and object counts. Assuming an annual replacement rate of 10% for constellation satellites, approximately 12000 satellites would be involved in a transecting maneuver (raising/deorbit) per year. These transecting satellites generate tens of thousands of additional conjunctions as they progress across many hundreds of kilometers of altitude over many weeks. Assuming a strategy in which the collision avoidance maneuver is shared equally between the satellites involved, the amount of ΔV required to minimize collision risk was estimated to be 3-5 times that of what is needed to operate in the current space environment, requiring an average of 62 m/s of annual ΔV budget for each spacecraft for just avoidance maneuvers. For some constellations, an additional 5% allocation specifically for collision avoidance maneuvers during transects may be required.

The simulations suggest a future space environment that will require a new level of monitoring and information exchange in order for all constellations and independent satellite operators to coexist safely. The current simulations made a number of simplifying assumptions that will continue to be improved upon in future work. This includes more robust position covariances (which directly impact Pc calculations), constellation dependent station-keeping and orbit raising/deorbit parameters, and fragmentation (consequence) estimates. The simulation tool also allows for rule-based maneuvers for active satellites to explore ways to determine which satellite should maneuver, and can implement both low-thrust and impulsive avoidance and raising/deorbiting trajectories. These aspects can all be used to test various hypotheses on how new policy or coordination ideas might impact the space object population. Experiments with maneuver lead times, maneuver priority, deorbit timelines, and operational orbit planes may lead to improved methods for operating in a dense future space environment.

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