THE IMPACT OF NEW TRENDS IN SATELLITE LAUNCHES ON THE ORBITAL DEBRIS ENVIRONMENT

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ABSTRACT

The main goal of this study is to examine the impact of new trends in satellite launch activities on the orbital debris environment and collision risk.

As a foundation for the study, we developed a deployment scenario for satellites and associated rocket bodies based on publicly announced future missions. The upcoming orbital injection technologies, such as the new launch vehicles dedicated for small spacecraft and propulsive interstages, are also considered in this scenario. We then used a simulation tool developed in-house to propagate the objects within this scenario using variable-sized time-steps as small as one second to detect conjunctions between objects.

The simulation makes it possible to follow the short- and long-term effects of a particular satellite or constellation in the space environment. Likewise, the effects of changes in the debris environment on a particular satellite or constellation can be evaluated. It is our hope that the results of this paper and further utilization of the developed simulation tool will assist in the investigation of more accurate deorbiting metrics to replace the generic 25-year disposal guidelines, as well as to guide future launches toward more sustainable and safe orbits.

1. INTRODUCTION

Starting from the launch of the first artificial satellite in 1957, spaceborne technology has become an indispensable part of our lives. More than 7,000 satellites have been launched into Earth orbit since then, contributing significantly to our understanding of space and Earth, and making our life easier [1]. Unfortunately, these systems, similar to any other system on Earth, do not have an infinite lifetime, therefore they will stop functioning once they are out of fuel or one of their systems fails. Currently, only around 1,400 satellites in orbit are operational [2].

During the early space age, it was not considered what would happen to the satellites once they become nonoperational. No measures were implemented to retrieve or dispose them. This resulted in an unnecessary accumulation of retired spacecraft in Earth orbits. Not only satellites contributed to the increase of the orbital density, but also the upper stage engines, which carried the satellites to orbit, fragments from engine exhausts and many other human-made objects.

Today, the space community is aware of the orbital debris and the problems it causes. A worldwide system of ground-based radars, telescopes, along with space-based sensors is utilized for tracking and cataloging orbital objects. The SpaceTrack database is maintained by the Joint Space Operations Center (JSpOC), part of the U.S. Strategic Command. Conjunction warnings are provided by the JSpOC to space operators in order for them to execute collision avoidance maneuvers. Before a launch vehicle lifts off, its trajectory is checked against the trajectories of orbital objects to avoid any collisions. [3]

Unfortunately the number of fragments in specific orbits is so high that accidental collisions are unavoidably producing more debris pieces than the rate of debris to fall naturally back to Earth due to atmospheric drag. A 1978 article [4] by Donald Kessler and Burton Cour-Palais discussed, for the first time, this potential of orbital debris becoming self-perpetuating; this phenomenon has been addressed as the "Kessler syndrome" in the literature since then.

Beside the technical challenge of cleaning up orbital debris, one of the main reasons that cause the hesitation and abstention to initiate the implementation of mitigation and remediation operations are the economic uncertainties. Although the space community agrees that space debris is threatening the orbital assets, decision makers still do not have a clear understanding of whether the additional cost originated from orbital debris on space operations exceeds the cost of implementing active or passive remediation projects.

There are four major reasons which cause the increase of the number of artificial objects in Earth orbit:

- Injection of new objects into the orbit
- Explosion of on-orbit objects (due to thermal effects on residual propellants and pressurants)
- Accidental collisions between on-orbit objects
- Intentional destruction of on-orbit objects

Until recent years, the majority of the orbital break-ups (i.e. more than 200 break-up events to date) were caused by explosions; these explosions were the prevalent cause of orbital debris [5]. However, their effect has become less pronounced due to passivation techniques which eliminate stored energy (i.e. using all the fuel), thus reducing the chance of a breakup [6]. Today, the primary driver of orbital debris is the accidental collisions between objects located in highly crowded orbits. Even simulations assuming no future launches pinpoint a cascading effect. They show that the number of objects and collisions will increase in the absence of remediation activities (i.e. removal of five objects with high mass and collision probability per year from orbit) [7].

However as a no-launch scenario is unrealistic, the satellite industry is likely to grow with more and more start-up companies having been established around the globe. Currently several consulting companies prepare forecasts to estimate the number of satellite launches [8]. However these forecasts do not take into account the orbital parameters for these satellites, nor do they include the other debris-creating factors (i.e. rocket bodies) which are critical for the accuracy of an orbital debris simulation. For this reason, we aim to create our own deployment scenario and then use our simulation tool to propagate their orbits into the future and examine the impact of new trends in satellite launch activities on the orbital debris environment and collision risk.

Section 2 and Section 3 explain our approach to create the scenarios for satellites and rocket bodies, respectively.

2. SATELLITE LAUNCHES

Since the 1960s, the annual number of payloads launched into Earth orbit was around 100-150 without large deviations. Fig. 1 represents this using the data from SpaceTrack database. The blue lines in the graph represent the number of payloads injected into Low Earth Orbit, LEO, (i.e. below 2000 km apogee) in the respective year and the red lines indicate the payloads located at higher altitudes. Due to the past stability of injection rates, most of the state-of-the-art long-term orbital debris projections record the launch activities 8- or 10-years before the start of their simulation and repeat that launch cycle consecutively for the entire simulation period.

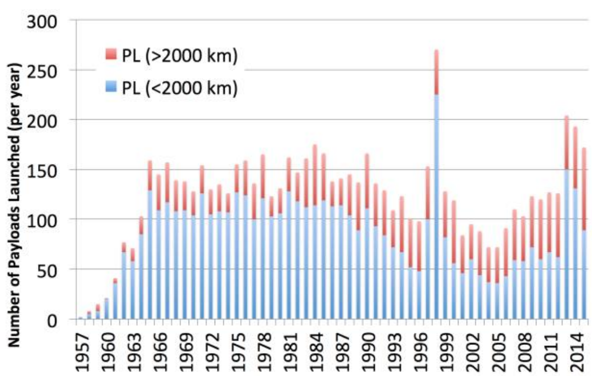

Figure 2-1 - Number of Payloads Injected into Orbit

In recent years, the satellite market has been undergoing a major evolution with new space companies replacing the traditional approach of deploying a few large, complex and costly satellites with a multitude of smaller, less complex and cheaper satellites. This new approach creates a sharp increase in the number of launched satellites and so the historic trends are no longer representative. The early effects of this change can already be observed in the right-most three bars of Fig. 1 representing the years 2013, 2014 and 2015. However, according to our research, the actual boom in small satellite market is likely to happen in the upcoming years.

The only way to make more realistic future predictions in such an emergent, thus unstable, environment is to put together the numbers from an up-to-date market analysis and try to estimate the trend. Since the orbital debris is more of a critical problem in LEO compared to higher altitudes, and since the recent changes in the satellite market is predominantly related with LEO missions, our study is dedicated to develop a scenario for LEO injections.

To develop this scenario, we systematically gather available data on future launches and collect it in a database. We aim to build a database that covers all the publicly available launch related information regarding the companies which intend to launch satellites into LEO between 2016-2030. These companies and/or constellations include, but are not limited to: Blacksky, CICERO, EROS, Landmapper, Leosat, Northstar, O3b, OmniEarth, OneWeb, OuterNet, PlanetIQ, Planet Labs, Radarsat, Terra Bella (formerly Skybox), SpaceX and Spire.

Data is gathered either through direct contact with the company or from online resources (i.e. company press releases and published interviews). Collected data includes: statements on the number of launches for each year between 2016-2030; the target orbits the constellation will be distributed to; and spacecraft mass and area. Whenever data are not available, estimations are made considering the constellation's purpose and company's previous missions, if any. The database also takes into account possible newcomers into commercial Earth observation and telecommunication markets (as additions), as well as the replenishment launches (as extrapolations) of the current and upcoming constellations to keep them operational. We are aware that it is unlikely that all of these companies will survive, however our model assumes a thriving "New Space" economy which would be a worst-case debris scenario.

Table 2-1 - Constellation Launch Data (2016-2020)

(values indicated as "u" refer to satellites in the respective CubeSat form factor; underlined values are our own estimates)

Constellation	Apogee (km)	Perigee (km)	Incl. (deg)	Mass (kg)	Area (m^2)	2016	2017	2018	2019	2020
Commercial Remote Sensing & Weather Tracking										
Landmapper-BC (Astro Digital)	600	600	SSO	6u	6u	2	4	4		
Landmapper-HD (Astro Digital)			SSO	16u	16u	2	6	6	6	
GRUS (Axelspace)	675	675	SSO	80	0.4		3	10	10	10
BlackSky Global	450	450	40-55	50	0.8	6	18	18	18	
World View (Digital Globe)	620	620	98	2800	2.5	1				
Digital Globe & Taqnia Space								3	3	
CICERO (GeoOptics)	650	650	SSO	104	1	6	6	12	*4*	*4*
HOPSat (Hera Systems)			SSO	12u	12u	9	10	10	10	9
HyspecIQ	500	500	SSO	600	1.4			*2*		
EROS (ImageSat)	500	500	SSO	350	1		1			*1*
Radarsat Costellation Mission (MDA)	592.7	592.7	SSO	1400	2			3		
NorthStar (NorStar Space Data Inc.)			SSO	750	0.15			*10*	*10*	*10*
OmniEarth	680	680	98	100	0.5				*18*	
PlanetIQ	800	800	72	25	0.01	2	10	6		*6*
Planet Labs	400	400	0	3u	3u	250	*75*	*75*	*75*	*75*
Satellogic	500	500	SSO	35	0.18	6	19	*50*	*50*	*50*
Spire	550	550	0	50	0.03	50	50	*50*	*50*	*50*
Terra Bella	600	600	0	120	0.4	2	5	5		*8*
Generation 3 (UrtheCast)			0	100	0.5				8	8
Other Remote Sensing & Weather Sat.			0	40	0.15			*25*	*50*	*80*
Commercial Telecom										
Iridium NEXT	780	780	86.4	50	0.2	32	40			
LeoSat	1430	1430	0	100	0.5				54	54
O3b	8062	8062	0.1	700	1.5		4	4	*8*	*8*
OneWeb	1200	1200	0	150	0.7			320	330	100
OuterNet	200	200	0	1u	1u	*10*	*12*			
SpaceX	1100	1100	0	200	0.8				300	300
Other Telecom Satellites			0	100	0.5				50	80
Non-Commercial Satellites										
All non-commercial			0	1500	1.5	*115*	*125*	*130*	*135*	*140*
					TOTAL:	**493**	**388**	**743**	**1189**	**993**

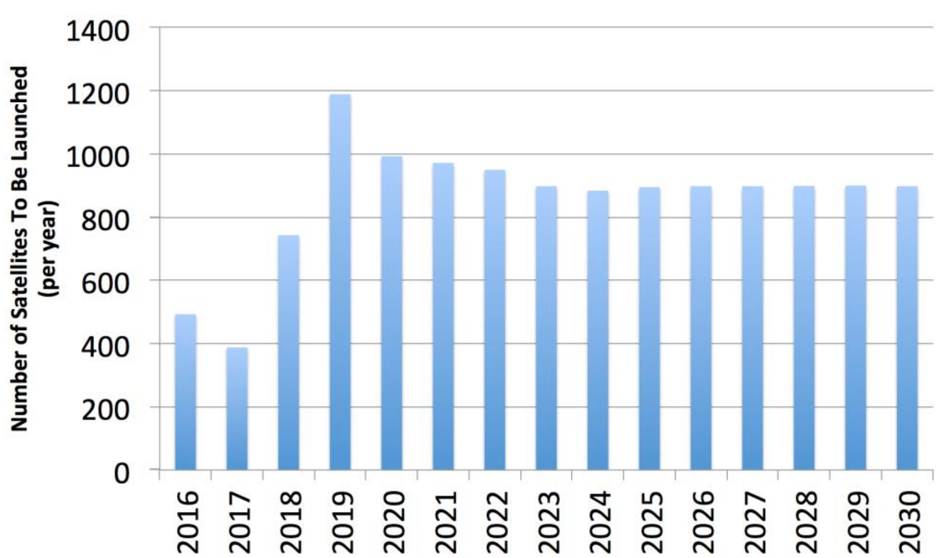

Figure 2-2 - Scenario for Satellites (2016-2030)

Tab. 2-1 shows a summary of our database for the period 2016-2020. Beyond 2020, most of our data has been calculated for replenishment launches, therefore are extrapolations of the first five years. The numbers indicated with underlined italic fonts in Tab. 2-1 are our estimations. Fig. 2-2 shows a summary graph generated from the database for the time interval 2016-2030.

As seen from Tab. 2-1 and Fig. 2-2, the main drivers of the sharp increase are the constellations for telecommunication (i.e. OneWeb and SpaceX). If the installations of these constellations are carried on as announced, these two alone will provide half of the annual launches starting from 2018.

3. LAUNCHED ROCKET BODIES

As aforementioned, satellites are not the sole source for space debris; the rocket bodies that carry them into orbit also contribute to the orbital debris problem. Fig. 3-1 shows the SpaceTrack data for the annually cataloged rocket bodies. This graph illustrates the number of rocket bodies injected into orbit per year peaked in 80s and decreased once satellites became smaller and shared launches popularized, stabilizing around 75 rocket body/year for the last 15 years. Around half of these bodies were positioned at LEO altitudes.

As a cross-check, Tab. 3-1 shows the number of LEO launches for the last five years [9]. Roughly half of the R-7 launches indicated in the table were missions that carried crew and cargo to the International Space Station. It is worth mentioning that the numbers given per year in Fig. 3-1 are not identical to the number of launches in that specific year in Tab. 3-1. This is due to the fact that for some of the launches, there are multiple upper stages remaining in orbit. Conversely, in some missions, the rocket bodies re-enter the atmosphere immediately after the deployment of their payloads; such objects may not be included in the SpaceTrack catalog.

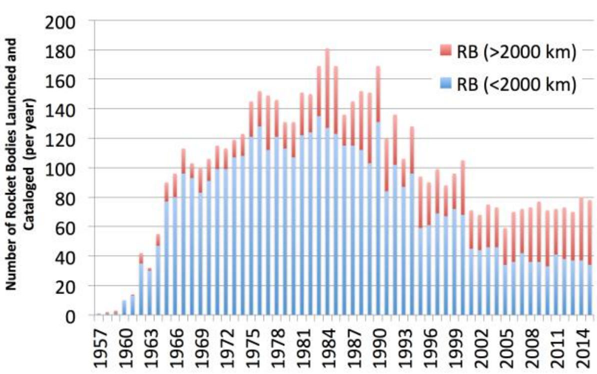

Figure 3-1 - Number of Rocket Bodies Injected into Orbit and Cataloged

Table 3-1 - Number of Successful Launches (LEO only)

Launch Vehicle	2011	2012	2013	2014	2015
R-7 (Soyuz/Molniya)	12	12	13	15	11
Long March)	9	10	10	13	10
Atlas 5	2	2	2	2	3
Ariane 5	1	1	1	1	0
Falcon 9	0	1	2	3	3
Delta 2	2	0	0	1	1
Delta 4	1	1	1	1	0
H-2A	2	1	1	2	2
H-2B	1	1	1	0	1
PSLV	2	2	1	1	3
Antares	0	0	2	2	0
Dnepr	1	0	2	2	1
Rokot	0	1	4	2	2
Vega	0	1	1	1	2
Strela	0	0	1	1	0
Kuaizhou	0	0	1	1	0
Minotaur 1	2	0	1	0	0
Uhna	0	1	0	0	0
Safir	1	1	0	0	1
Pegasus XL	0	1	1	0	0
Shavit	0	0	0	1	0
Epsilon	0	0	1	0	0
Angara	0	0	1	0	0
Zenit	1	0	0	0	0
Sum	**37**	**36**	**47**	**49**	**40**

Considering Fig. 3-1 and Tab. 3-1, it is reasonable to estimate that typically 40 rocket bodies have been injected into LEO every year since 2005. However, our analysis on the SpaceTrack catalog shows that some portion of these rocket bodies decays within a couple of days after their launch date and it is not meaningful to consider those in our long-term debris simulations. To find out this ratio, we divide the catalog into six 10-year periods and perform a histogram analysis within these blocks. Tab. 3-2 shows that, historically, 25% to 40% of the rocket bodies injected into orbit re-entered the atmosphere within 10 days. This temporal analysis reveals another interesting result: for the last 50 years, a shrinking percentage of the rocket bodies decayed soon after their launch and hence contributed more to the orbital debris problem. However, with the expectation of stricter rules and a potential use of reusable launchers, we build our scenario around an assumption that 30% of the rocket bodies will be de-orbited in the future and 70% will be left for their natural decay.

Table 2-2 - Percentage of rocket bodies decayed in 10 days after their launch date, per decade

	1957 - 1966	1967 - 1976	1977 - 1986	1987 - 1996	1997 - 2006	2007 - 2006
# of RB deorbited in 10 days	94	417	495	357	154	110
Total # of RB cataloged	315	1062	1267	1012	583	445
Ratio of RB deorbited in 10 days	30%	39%	39%	35%	26%	25%

Having all these historical data, it remains difficult to estimate future trends for the number of rocket body deployments into orbit. Since the satellites are getting smaller in size and weight, more of them fit into a launch vehicle. Therefore, the boom in the small satellite market is unlikely to trigger a sharp increase in demand on the launch sector.

Conversely, there is a widespread effort to enhance orbital injection capabilities and accuracy. A long list of companies such as Microcosm, Rocket Lab, Firefly Space Systems, Sierra Nevada Corporation and Arca Space Corporation are developing new launch vehicles dedicated for small satellites. There are other companies which intend to develop interstages with propulsive capabilities, which will allow the deployment of satellites into their desired orbits beyond the restrictions of the launch vehicle used.

Considering these aspects as a whole, we decided to correlate the rocket body deployment scenario with our satellite deployment scenario explained in Section 2. For this purpose, we analyze rideshare missions (i.e. missions containing at least one secondary payload with the primary payload) performed in the last 15 years to find out how many payloads were aboard in each of those launches. Tab. 3-3 lists the main launch vehicles used in these missions. As seen from the table, an average of six payloads was carried per mission. However, there had been launch campaigns which carried more than 30 payloads to space. In May 2016, a Falcon 9 rocket is expected to carry 88 satellites utilizing the Sherpa deployer.

Considering these advancements, we find it reasonable to assume that a LEO launch campaign, on average, will carry nine satellites into orbit in the near future. We also assume that only 70% of the rocket bodies will stay in orbit as explained above. Within this framework, Fig. 4-1 shows the scenario for rocket bodies to be included in our debris simulations. The apogee, perigee and inclination data for these objects were estimated in

Table 3-3 - Average Number of Satellites Launched During Shared Missions

Launch Vehicle	Number of Secondary Payloads Launched	Number of Launches	Average Number of Payloads Launched per Shared Mission
Dnepr	122	12	10.2
PSLV	52	15	3.5
Atlas V	46	4	11.5
Minotaur 1	46	7	6.6
HII-A	27	6	4.5
Soyuz-2	23	5	4.6
Long March	22	5	4.4
Falcon 9	19	3	6.3
Delta II	11	4	2.8
Vega	11	2	5.5
TOTAL	**379**	**63**	**6.0**

correlation with the information gathered on announced spacecraft launches and the historical trends.

4. SIMULATIONS

The developed deployment scenario feeds into a simulation tool that is capable of propagating the objects with variable-sized time-steps as small as one second. An automated script pulls the necessary parameters from the database and converts them into a suitable format to be fed into the simulation. Launch epoch dates were assigned randomly within the launch year for each constellation from the database. A maximum of 15 objects are allowed for a single launch. Additional parameters, i.e. area-to-mass ratios, drag coefficient and reflectivity, are assigned to each object according to their physical specifications. For modeling 2030 onward, we chose to build the scenario extrapolating the 2016-2030 data on yearly basis. Over the course of the run, the software also detects collisions; additional debris objects are then created according to the NASA breakup model and are then fed back into the simulation framework. More detailed information about the simulation tool can be found in [10] and [11].

5. RESULTS

Fig. 4-2 shows the results of a single simulation run for the number of objects greater than 10 cm in LEO. This run uses an initial population from the SpaceTrack catalogue as of June 2015; additional objects are introduced to the population over time according to our deployment scenarios. Full collision functionality of the code is enabled.

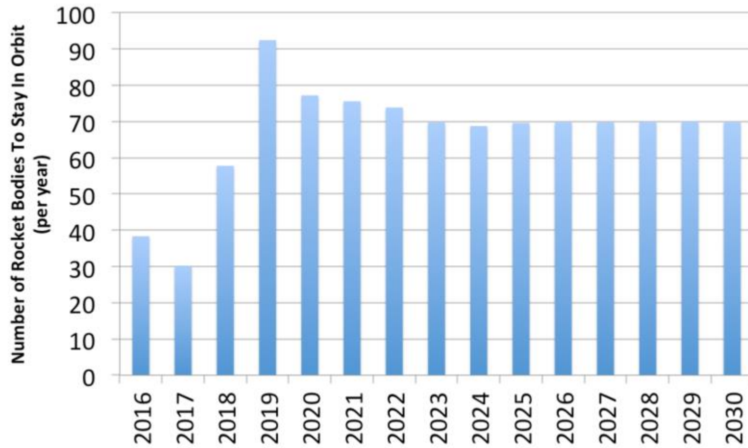

Figure 4-1 - Scenario for Rocket Bodies to Stay In Orbit (2016-2030)

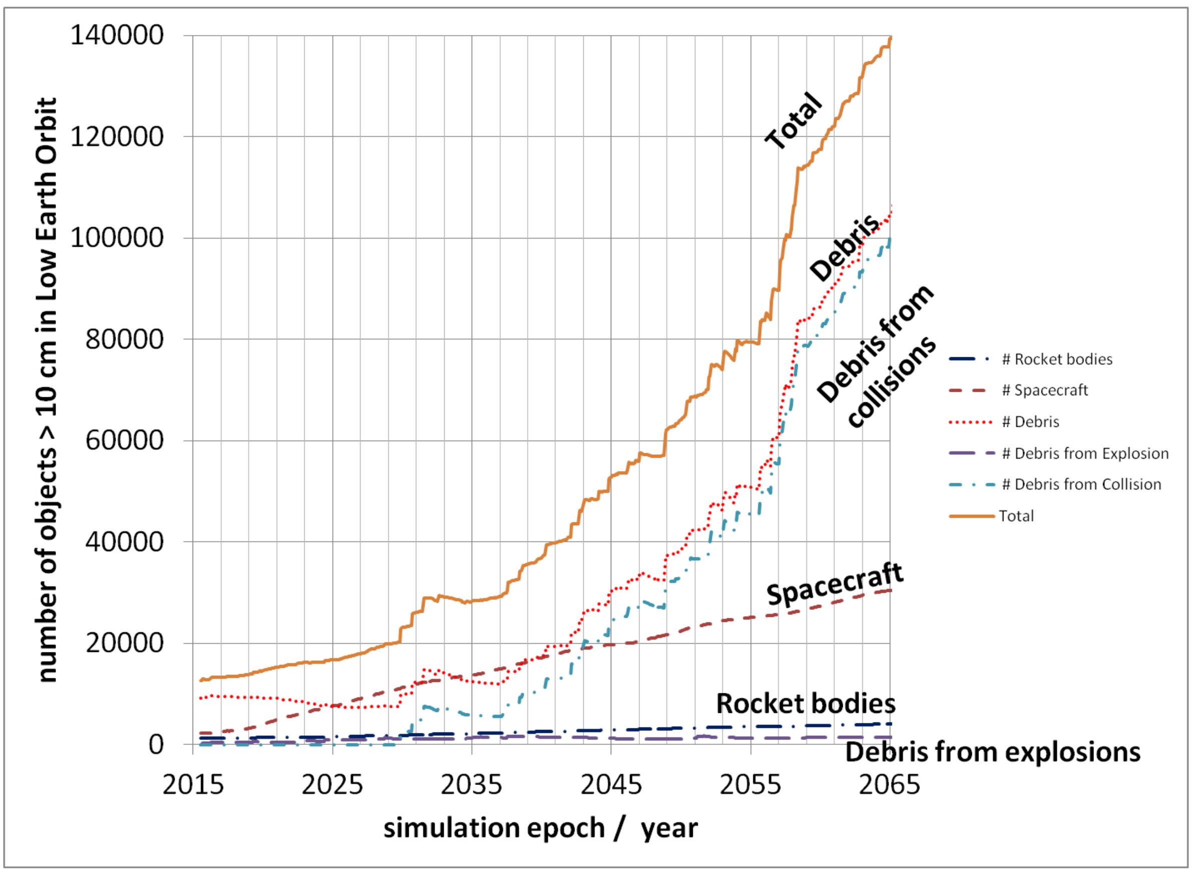

Figure 4-2 - Number of debris objects in LEO over time for a single simulation run using the deployment scenario.

In this (singular) simulation run, the first collisions occur in the late 2029-2032 timeframe. A portion of that debris decays between 2032 and 2036, but from 2036 collisions start to occur regularly, dominating the increase in object population.

In addition to the number of objects, the tool also tracks conjunctions, which are close encounters between space objects. Fig. 5-1 shows all detected conjunctions with a probability of collision P_c larger than 10^{-4}. In the given scenario, there are only 1126 in 2016, rising to a maximum of 179 thousand in 2062. The pronounced spikes are follow-up conjunctions after breakup events, when objects in a debris cloud are still close to each other. Fig. 5-2 shows only conjunctions involving at least one spacecraft and hence omitting the direct after effects of a breakup event. In this case, the number rises from 415 conjunctions with $P_c>10^{-4}$ in 2016 to 44 thousand in 2064. The consequence is that operators might be overwhelmed by those numbers and do not perform collision avoidance maneuvers.

6. CONCLUSIONS AND OUTLOOK

While a single run already provides interesting information, it is necessary to obtain error bounds and average projections with a full Monte Carlo treatment. This task is to be implemented in the future.

Examining the simulation results, the total number of particles to accumulate in different orbits can be monitored and the number of conjunctions can be tracked to assess the collision risks.

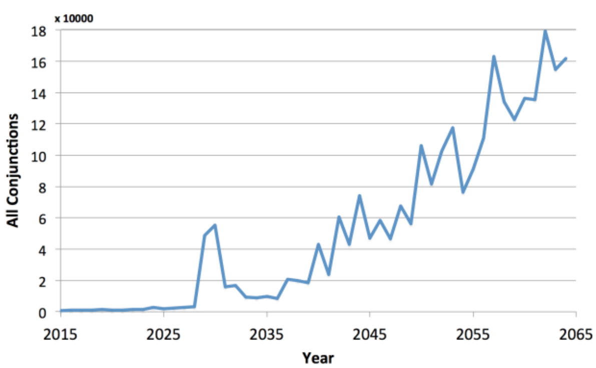

Figure 6-1 - Number of conjunctions with a probability of collision larger than 10^{-4} per year.

The simulation makes it possible to follow the short- and long-term effects of a particular satellite or constellation in the space environment. Likewise, the effects of changes in the debris environment on a particular satellite or constellation can be evaluated.

It is the authors' hope that the results of this paper and further utilization of the developed simulation tool will assist in the investigation of more accurate deorbiting metrics to replace the generic 25-year disposal requirement, as well as to guide future launches toward more sustainable and safe orbits.

7. ACKNOWLEDGMENTS

While this paper focuses on future launch activities, the data in Figures 4-2, 5-1 and 5-2 was produced using the simulation tool described in [10] and [11]. We would like to thank Bron Nelson and Fan Yang Yang who are the primary authors of those papers and the tool. We also would like to thank Roberto Carlino, Andres Dono Perez, Nicolas Faber, Cyrus Foster, Chris Henze, Creon Levit, Conor O'Toole, Jason Swenson and Wang Ting for their contributions.

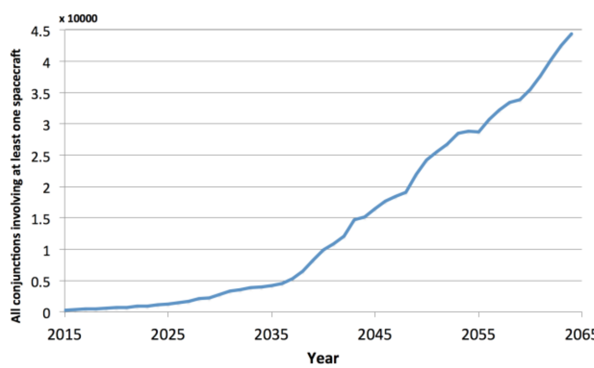

Figure 7-1 - Number of conjunctions involving at least one spacecraft , with a probability of collision larger than 10^{-4}, per per year

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