Examining Short-term Space Safety Effects from LEO Constellations and Clusters

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ABSTRACT

The large satellite constellations currently planned and deployed in Low Earth Orbit bear some similarities with the clusters of derelict objects abandoned in some altitude bands in LEO. Given the similarities between the two physical situations, a tool developed at IFAC-CNR for long-term constellation impact analysis is applied in two new ways: (1) focus on immediate (i.e., 1-20 years) effects from constellation deployment and execution and (2) apply to the accumulation of massive derelict objects in a restricted region of space (i.e., clusters). The intra-group collision probability caused by the repeated orbital crossing between the members of two selected constellations and of some of the clusters of objects in LEO are computed, cumulated over the time span of the analysis (20 years) and compared. While the collision probability obtained in the case of the constellation could be efficiently mitigated by proper management and operations (i.e., debris mitigation practices and collision avoidance), the high level of risk associated with the clusters of derelict uncontrolled objects cannot be avoided, unless pro-active actions are undertaken to remove the large targets from the space.

1 INTRODUCTION

Typically, the examination of how large satellite constellation deployments and operations might affect the space environment has focused on long-term environmental realities over centuries. This perspective provides valuable insights into the strategic evolution of the debris risk. While environmental stability is clearly an important measure, short-term (i.e., 1 - 20 years) space safety levels for current space systems is also important for all space faring entities.

Stemming from the long term evolution model SDM [1], a dedicated tool was developed at IFAC-CNR for long-term constellation impact analysis. Given the similarities between the two physical situations, the tool is now applied in two new ways: (1) focus on immediate (i.e., 1-20 years) effects from constellation deployment and execution and (2) apply to the accumulation of massive derelict objects in a restricted region of space (i.e., clusters). Risk calculations provide an opportunity to examine the relative importance of managing future large satellite constellations and existing large concentrations of massive derelicts.

In the next section, after a brief introduction on the large constellations to be deployed (or being deployed in Low Earth Orbit (LEO)) and on the clusters of derelict objects in LEO, the collision probability for these groups of objects will be computed and compared. The analysis provides a means to quantify and directly compare two potentially significant space safety concerns: large satellite constellations and clusters of massive derelict objects . On the basis of the shown results a number of conclusion will be presented.

The large constellations

In the next decades a number of large satellites constellations are expected to be launched in Low Earth Orbit. The huge number of satellites involved in these constellations poses new challenges to the space debris community at large. As currently envisaged, these large ensembles of satellites will fly in the already crowded LEO region and by their configurations they will orbit in restricted regions of space. Thus, the proper management of their launch, operations and disposal traffic will be essential to limit the impact of these space structures on the future evolution of the space environment. Table 1 summarizes the main systems being launched or planned for the next decades.

A large number of studies and papers have been produced in the last few years describing the issues related to the deployment of these satellite systems. The interested reader can refer to, e.g, [2][3][4] and the references therein.

Name	Altitude [km]	*i* [deg]	Orbital planes	Satellites
IRIDIUM NEXT	780	86.4	6	66
OneWeb	1 200	87.9	18	648
Starlink	550	53	72	1 594
Starlink VLEO	340	53	83	7 518
Kuiper (part 1)	590			784
Kuiper (part 3)	610			1 296
Kuiper (part 3)	630			1 156
Telesat (polar)	1 000	99.5	6	72
Telesat (inclined)	1 248	37.4	9	45

Table 1. Characteristics of the main large constellations planned or already in the deployment phase.

The clusters

Over half of the 10,500 rocket bodies and payloads ever deployed in space remain orbiting the Earth. Unfortunately, the story gets worse; over a third of this massive derelict population resides in the small sliver of space in the persistent portion of LEO between 600 and 2,000 km in altitude (called LEO HIGH). Objects with orbits totally below 600 km are considered to be in LEO LOW [5]. Fig. 1 depicts the accumulated mass of abandoned rocket bodies and defunct payloads over time for four specific orbital regions accentuating the residual debris-generating potential accumulated in LEO HIGH. Please note that the leveling off for mass is partially due to the fact that payloads deployed recently have not yet reached the end of their operational lifetime. In addition, LEO HIGH is not being used as much with new missions as LEO LOW so the leveling is partially a reflection of less use of that region relative to LEO LOW. For LEO LOW, atmospheric drag provides a cleansing mechanism for many of the objects but the objects in the lower portion of LEO HIGH will descend into LEO LOW over time due to atmospheric drag. The SEMI (for semi-synchronous, also known as Medium Earth Orbit) and Geostationary Orbits region (GEO) have many fewer objects and longer mission lifetimes so there has been little increase derelict hardware in those two other critical regions in Earth orbit in the last few years.

Worse yet, of the nearly 2,000 derelict massive rocket bodies and payloads abandoned in LEO, a quarter of these are contained within four, even more concentrated, clusters of very large objects centered at 775, 850, 975, and 1500 km that were largely populated between the years 1980 and 2000. Close approaches less than 1,000 m occur on average 1,000 times a year between objects within these three clusters.

In Cluster 850 (C850), conjunctions within 5 km occur on average of about once a day, with the closest miss over the last four years being 87 m with a relative velocity of typically 12 km/s. If a collision were to occur between two objects in this cluster, the catalog population could double in an instant with the liberation of roughly 16,000 trackable fragments and 200,000 or more of non-trackable particles potentially lethal in case of collisions (LNT). These events are so consequential because 18 of the 25 most massive objects in LEO were abandoned in orbit within a 45 km altitude span. The cluster centered at 975 km (i.e., C975) has about 60 conjunctions daily within 5 km and typically has monthly conjunctions that meet or exceed the probability of collision when Iridium-33 and Cosmos 2251 collided in 2009. Each of these events would produce about 4,500 trackable fragments and upwards of 60,000 LNT.

Table 2 summarizes the general characteristics, annual probability of collision (PC) between members of each cluster (i.e., cluster collision rate), and consequences from collisions in the four primary clusters. Note that C975 contains nearly four times the mass in the same altitude span as the proposed 588-satellite OneWeb constellation. Furthermore, OneWeb has a sophisticated constellation design and collision avoidance capability while the C975 cluster members have neither.

Table 2. Cluster characteristics highlight the debris-generating risk these collections of massive derelicts pose.

Center of Cluster (Span)	# of Objects and Mass (kg)	PC/yr and Probability of First Collision by 2019	Mass Involved in Typical Collision, kg	Debris Generated from Collision Trackable (LNT)	Comments
775 km (60)	101 ~100,000	~1/400 4%	~1,600 – 2,800	~4,500 (~60,000)	**Most operational satellites affected**
850 km (45)	75 ~208,000	~1/800 1%	~6,000 – 18,000	~16,000 (~200,000)	**Most consequential events**
975 km (115)	314 ~335,000	~1/90 11%	~1,600 – 2,800	~4,500 (~60,000)	**Most likely events**
1500 km (400)	73 ~96,000	~1/1200 0.5%	~3,200-3,600	~9,000 (~120,000)	**Most long-lived debris**

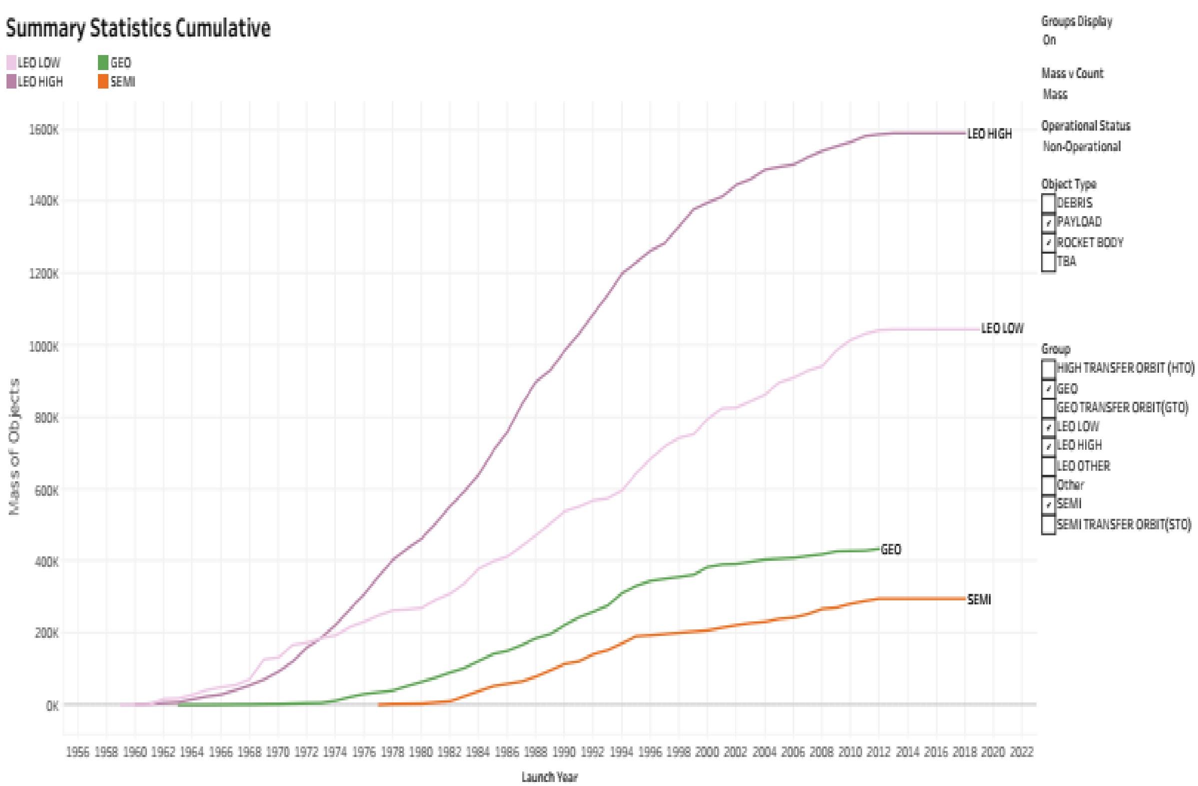

Fig. 1. The accumulated mass of intact derelicts in the upper region of LEO (i.e., LEO HIGH) is significant and is not being reduced via atmospheric drag. [Source: McKnight, D., Witner, R., and Arora, R., "Intact Derelict Deposition Study," IOC, Dec 2019.] (LEO HIGH is the higher part of LEO with perigee above 600 km and apogee below 2,000 km. LEO LOW are orbits under 600 km. SEMI is the semi-synchronous region from 18,000-24,000 km. GEO is geosynchronous orbit region from 35,586-35,986 km.)

2 THE MODEL AND THE COMPUTATIONAL METHODS

In the following simulations two constellations at different orbital altitude were considered. In particular, a high LEO constellation similar to OneWeb and a low LEO constellation similar to Starlink were selected from those listed in Tab. 1. Note that the chosen parameters are not supposed to be exactly equal to the “official”one thus, while for sake of simplicity we refer in the following to “OneWeb”and “Starlink”, the reader should interpret them as “OneWeb-like” and “Starlink-like” constellations.

The constellations are build considering the distribution of objects described in Tab. 1. A vertical spacing between the orbital planes over 50 km for both the constellations is considered. Therefore, the inclination of the different planes is slightly different and is computed in order to have a common precession of the right ascension of the ascending node, to keep the configuration of the constellation constant.

In the case of the constellations, the operational satellites are supposed to be controlled, thus the mean semimajor axis is kept constant while the angular elements of the orbit are propagated with an analytical model accounting only for the oblateness of the Earth (J2 term), in order to keep the overall constellation configuration.

Furthermore, in both constellations, we consider two different scenarios where either 5 or 8 failed satellites are added to the operational ones every year. The failed satellites are deposited in circular orbits within the constellation at a random altitude between the minimum and the maximum altitude of the orbital planes and with the angular arguments randomly chosen. The failed satellites are propagated with a full model considering all the relevant perturbations (gravity field up to 5x5, solar radiation pressure, air drag, third body).

In our analysis we consider 3 out of the 4 clusters described in Tab. 2: C1500, C975 and C775. For all the clusters, the orbital elements of all the objects are taken from the Two Line Element catalogue and the physical characteristics of each object (mass and area) are taken from the publicly available information. In the case of the clusters the full orbit propagation model is always used for all the objects.

Figure 2 shows the orbital distribution, in terms of altitude and inclination, of the ensambles of objects considered in our analysis. A few considerations are in order. First we note the compactness of the two constellations; a well known issue for these kind of systems, requiring a tight and well planned design and management. Then, in the case of the clusters we note how the two lower ones (C775 and C975) are both extremely compact in terms of altitude. Moreover, while C775 is all concentrated at the same inclination of about 74 degrees, C975 displays three different inclinations groups at around 65, 74 and 87 degrees, respectively. Note that, while the tight distribution in altitude is obviously responsible for an increase in the overall collision probability, conversely the dispersion in orbital inclination does not necessarily represent an advantage (w.r.t. the collision risk) since what matters here is the mutual inclination between the different orbital planes. This specific value might be increased by the distribution shown in Fig. 1 within the cluster C975. The highest cluster C1500 on the other hand shows a sparser distribution in altitude and two inclination bands.

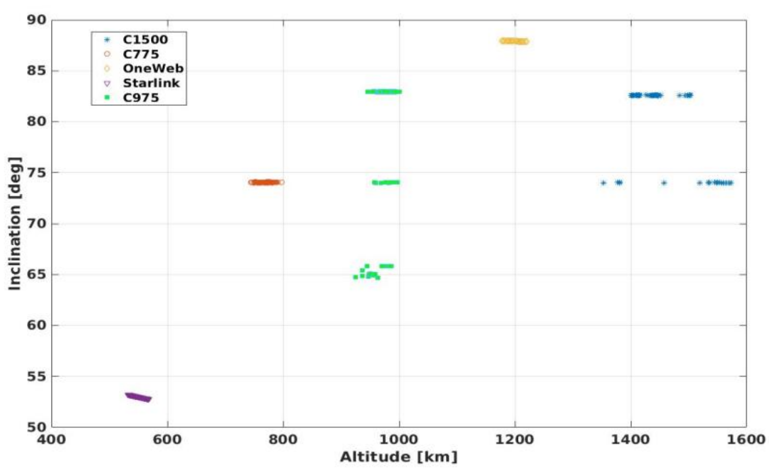

Fig. 2 Initial orbital distribution (inclination vs. altitude) of the population of objects examined in the paper.

The five groups of objects are evolved for 20 years by means of a branch of the SDM, long term debris evolution model [1]. Only the objects within each group are considered, i.e., there is no background population interacting with the constellations and the clusters, since we are interested here only in the self-generated collision risk within the groups. In the SDM model the CUBE [6] method is used to compute the collision probability at each orbital crossing. A default cube size of 1 km is used. The system is sampled at intervals of 0.05 days (i.e., 4320 seconds). At each sampling time, the collision probability between objects residing within the same cube is recorded and summed up to get the final values of the “cumulative collision probability”, shown in figures in the following section. In all the cases, also the orbital crossing happening within an enlarged cube with a size of 3 km are also considered and recorded to try to cumulate statistics for some of the cases with sparser events (in particular for the C1500). No collisions are performed in the simulations. That is, irrespective of the value of the computed collision probability, no Poisson distribution is invoked to draw and simulate actual fragmentation events. Note that, for the constellations, only the orbital crossings involving at least one uncontrolled (failed) spacecraft are recorded. That is, all the crossings between two controlled operational satellites are considered “safe” and “avoided by design”, thus are not included in the cumulated quantity displayed in the figures in the next section.

For all the simulated scenarios, 500 Monte Carlo runs are performed, randomizing the initial mean anomaly of the objects. Note that, in the constellation cases, while the initial mean anomaly of the failed uncontrolled satellites is fully randomized (between 0 and 360 degrees), the mean anomaly of the constellation satellites are only randomized within a tiny interval (again to keep the overall constellation configuration).

3 RESULTS

The panels of Fig. 3 show the comparison of the cumulative collision probability for the two constellations in the case with 5 (blue line) and 8 (red line) failed satellites injected every year in the simulation. The left panel refers to the OneWeb-like constellation while the right one to the Starlink-like one. We repeat again that in the plots only the crossings involving at least one failed satellite are considered. Thus, the majority of the recorded crossings involve one active satellite and a failed one. On average, for our OneWeb-like constellation about 8 % of the crossings in the 5-failed case and 19 % in the 8-failed case are between two uncontrolled failed spacecraft. For the Starlink-like cases, only about 1 % of the crossings in the 5-failed case and 3 % in the 8-failed case are between two uncontrolled failed spacecraft. It worth stressing already at this point, that an efficient collision avoidance system is supposed to be in place for the operations of the mega-constellations. Therefore most (if not all) the crossings involving an active satellite should not lead to catastrophic collision events. Notwithstanding the higher number of satellites and the smaller separation in altitude between the orbital planes, the cumulative values shown in Fig. 3 are comparable for the two constellations. This is mostly related to the orbital altitude of the two groups. Since we are considering only the risk posed by the uncontrolled satellites, while the failed satellites in Oneweb-like remain inside the operational envelope for all the time span of the simulation (no drag is *de-facto* acting at 1200 km of altitude), the failed satellites in Starlink-like tend to leave the operational altitude quite fast due to the drag, thus lowering the cumulative risk over the simulation time span.

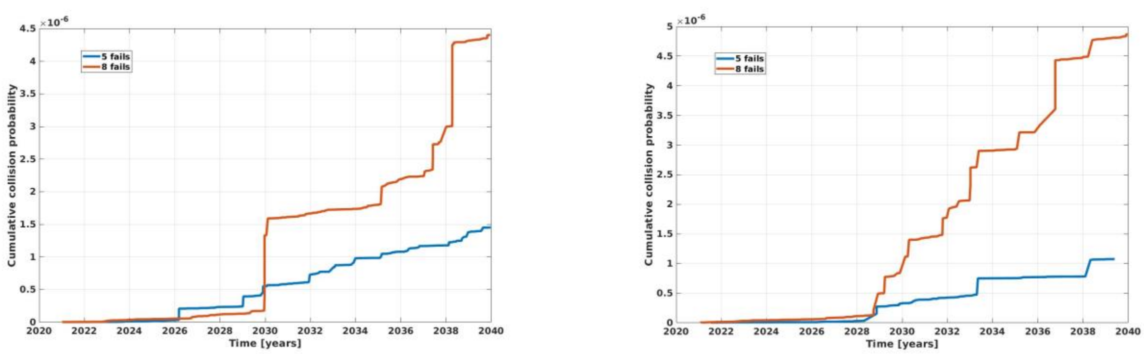

Fig. 3. Cumulative collision probability for the Oneweb-like (left panel) and the Starlink-like (right panel) constellations in the cases with 5 failures per year (blue line) and 8 failures per year (red line). Note that the panels have different y-scale to avoid a crushing of the lines in the right panel.

The two panels of Fig. 4 show the cumulative collision probability for the three clusters under exam. The left panel shows the results for the default case of a 1km-size cube and the right panel refers to the 3 km-size cube (used here to discriminate the low C1500 results). As it is apparent from the plots of Fig. 4, taking into account Tab. 2 and Fig. 2, the tight altitude concentration and the numerousness of the C975 cluster makes it significantly more exposed to the risk of a mutual collision by its members. Conversely, C1500 is sparser in altitude and less populated, thus it accounts for the lowest value of the cumulative collision probability. C775 shows an intermediate behavior again consistent with its characteristics as described in Tab. 2 and Fig. 2.

A comparison between the results of the constellations and of the clusters is shown in Figs. 5 and 6. For the constellations the cases with 8 failures are considered. In particular, Fig. 5 shows the cumulative probability on a linear (left panel) and logarithmic (right panel) scale, for the case with the standard cube dimension of 1 km while Fig. 6 shows the same quantities for the 3 km-size cube. From the direct comparison it emerges clearly the overwhelming risk related to C975 with respect to all the other cases. The cumulative collision probability for C975 is more than 3 times higher than for any of the other groups considered and is steadily growing due to the repeated orbital crossings and close approaches between the members of the cluster, with no natural disposal mechanism acting at that orbital altitude.

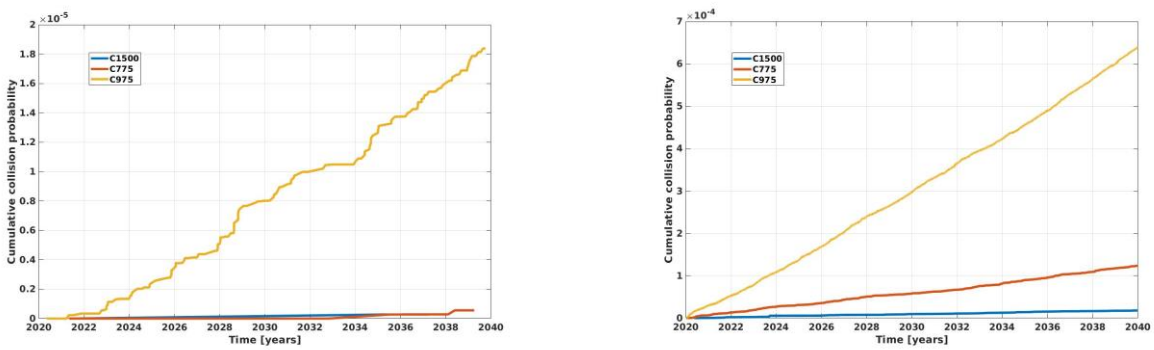

Fig. 4. Cumulative collision probability for the three clusters. The blue line refers to C1500, the orange line to C775 and the yellow line to C975. The left panel shows the results for the 1km size cube, while the right panel refers to the 3 km size cube results.

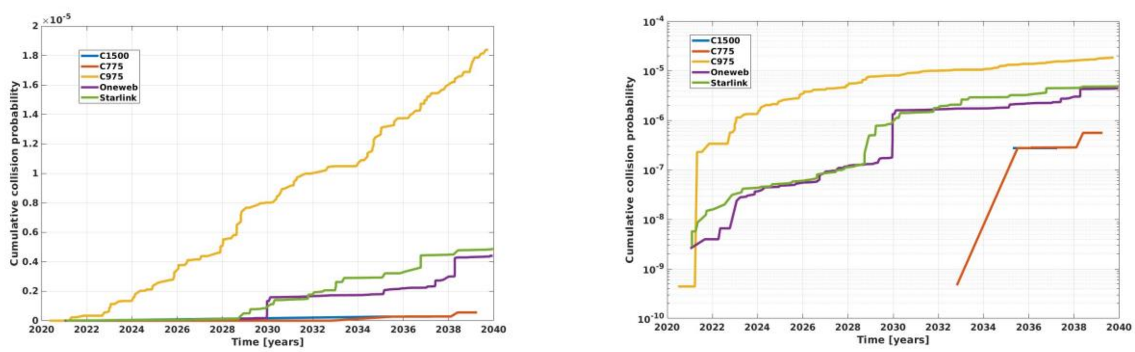

Fig. 5. Cumulative collision probability for the three clusters and the constellations, in the scenario with 8 fails per year. The left shows the results in a linear scale, while the right panel uses a logarithmic scale.

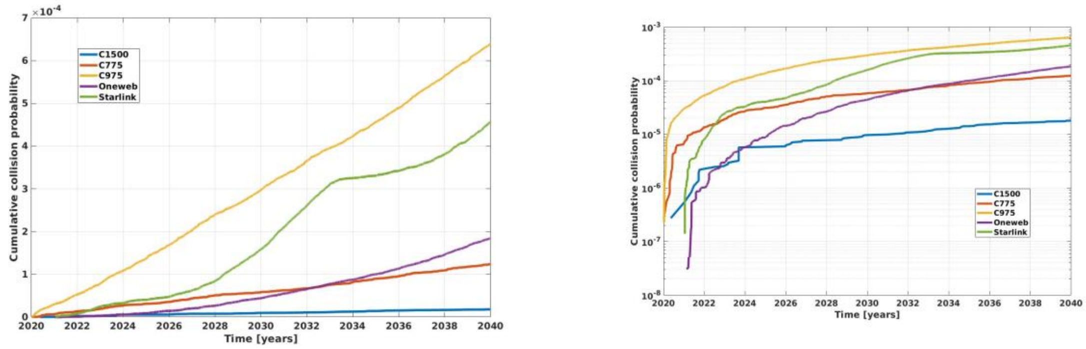

Fig. 6. The same as in Fig. 5, with a cube size of 3 km.

The two panels in Fig. 7 show the *superior limit* of the distance between the objects in each orbital crossing recorded in the 500 MC runs for the C975 (left panel) and C775 (right panel) clusters, respectively. The use of the terms *superior limit* is related to the use of the CUBE method. As mentioned above (see [6]) the method relies on a statistical time sampling of the orbiting population. At each time interval a check is done to see if two objects are found within the same cube. If this is the case, the collision probability between these two objects is computed (by means of a particle-in-a-box equation). Therefore, the recorded distance might not be (and in general, is not) the closes approach distance between the two objects, because the instant of the time sampling is not necessarily the instant of the close approach. Therefore, what we can say is that the "true" close approach distance must be lower or at most equal to the distance recorded at the sampling time. To find the "true" close approach distance we should perform a backward/forward propagation in a neighborhood of the sampling time. The used SDM model is designed to do this (e.g., [7]) but this feature is not deemed useful in the present statistical analysis. Notwithstanding what is explained above, we note, especially in the C975 case, a very large number of close approaches within several hundred meters, with the median value of the superior limit for C975 found at about 600 meters.

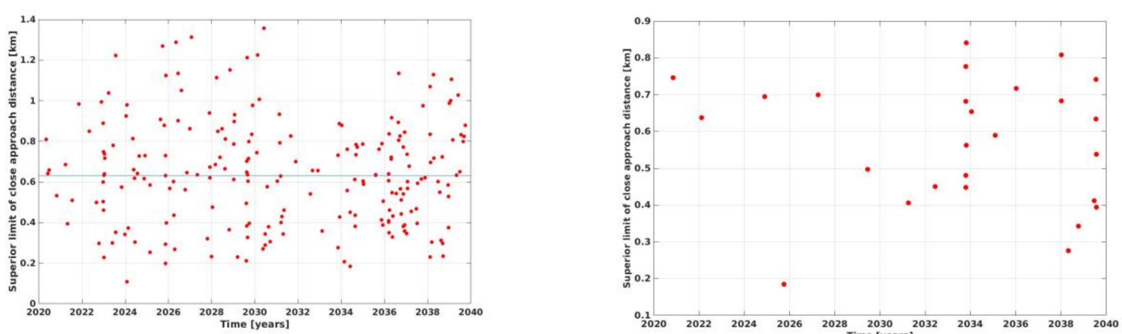

Fig. 7. Superior limit of the close approach distances (see text for details) for the C750 (left panel) and C975 (right panel) clusters. The blue line in the right panel shows the median value of the distances.

4 CONCLUSIONS

The above analysis shows the risk associated to the “accumulation” of objects in a comparatively restricted region of space. As Nature teaches us, a large number of objects tightly packed in a similar orbital zone finally gives way to multiple collisions, such as, e.g., in the asteroid belt, unless the orbits of the involved bodies are protected from one another by some kind of resonant behavior, such as, e.g., the mechanism preventing Pluto from impacting against Neptune.

In the case of the artificial satellites in Earth orbit we analyzed the case of “controlled” ensambles of objects, i.e. the proposed large constellations in LEO, and “uncontrolled” groups of derelict massive objects, the “clusters”. The results of the previous sections tell us that, as mentioned in previous works (e.g., [2][3][4][7]) the failed uncontrolled satellites can represent a significant risk for the large constellation, but this kind of risk can be mitigated by an efficient management of these systems. An operational service of accurate monitoring leading, when needed, to collision avoidance maneuvers can minimize the risk of collision against large trackable targets. In principle, as mentioned in the previous section, if we assume a perfect collision avoidance service, most of the orbital crossings in the constellation cases should not enter in the cumulative collision probability computation but would “only” represent a nuisance for the constellation operation. On the other hand all the members of clusters considered in this analysis are stranded uncontrolled spacecraft for whom no maneuver would be possible (some kind of experimental collision avoidance procedures have been proposed for this non-maneuverable objects but they are still to be tested and validated [8]) .

Moreover, while, as described in a series of papers [9][10], a number of catastrophic collisions inside a constellation would pose an additional risk to the operational satellites, it is worth stressing that the satellite envisaged for the large LEO constellations tend to be comparatively small, thus leading, in case of fragmentation, to a limited number of debris limiting the long term consequences of this event [11]. On the other hand, the members of the clusters are usually very large spacecraft and upper stages (of the order a few tons). Any catastrophic fragmentation involving one of these giant objects would result in a massive cloud of fragments which would also be long lived due to the high orbital altitude, thus representing a significant long term risk for the environment [11][12] .

Finally, we remind that, at difference from our previous studies, we on purpose did not consider any background population of debris interacting with the constellations and the clusters, since we are interested here only in the self-generated collision risk within the groups. In this respect, all the above results can be considered “best cases” results since all the objects considered in our analysis would also be subject to the risk of colliding with other background objects.

In conclusion, it is worth stressing again that, due to the extended orbital lifetime of the objects in the clusters, the pace of the growing collision probability could only be reverted by an active removal of those massive targets from space.

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