Kessler Syndrome: System Dynamics Approach

Jakub Drmola[1], Tomas Hubik[2]

[1]Division of Security and Strategic Studies at the Faculty of Social Sciences of Masaryk University in Brno, Czech Republic
[2]Department of Theoretical Computer Science and Mathematical Logic at the Faculty of Mathematics and Physics of Charles University in Prague

[1]Jostova 10, 602 00 Brno, Czech Republic
[2]Malostranskw namesti 25, 118 00 Praha 1, Czech Republic

[1]jdrmola@mail.muni.cz
[2]hubik.tomas@gmail.com

The present paper explores the Kessler Syndrome (the potentially catastrophic accumulation of debris in the Low-Earth Orbit) through System Dynamics methodology. It models satellites and three classes of debris, their fragmentation, interactions and gradual decay over 50 years. It presents three scenarios: a) a "business as usual" approach, which leads to exponential accumulation and growing rate of satellite losses, but no catastrophic chain reaction; b) a conflict with a large-scale deployment of Anti-Satellite Weapons, leading to accelerated accumulation and losses, but still no chain reaction; and c) cessation of all LEO satellite launches, illustrating high inertia of the system, which continues to produce more debris. Both b) and c) take place in 2040. The paper demonstrates the gravity of the situation and the necessity for a sustainable long-term solution, as orbital debris poses a threat to our future space operation even without triggering a catastrophic chain reaction.

Keywords: System Dynamics, Kessler Syndrome, LEO, Satellites, Orbital Debris, Anti-Satellite Weapons, Debris Evolutionary Model

Introduction

There are over 29,000 man-made objects greater than 10cm in size in the orbit. These objects include defunct satellites, pieces of spacecraft, mission related debris and other pieces of space junk. The number of these objects is continuously growing due to the continuing launch activity and spontaneous space collisions and breakups. Atmospheric drag force is not sufficient to stop this trend. Methods and techniques on how to stop this growth are becoming a more and more relevant topic when talking about space programs. Precise tracking of all these objects is critical for any space mission to succeed.

As the number of objects in the orbit increases, the likelihood of collisions increases as well. A typical space object experiences several close flybys per day. By close we mean a couple of kilometers in distance. Each flyby has a certain probability of becoming a collision. Every collision creates more debris making the probability even higher in the future. When the number of objects in the space is sufficiently high, there is a chance of forming a self-sustaining collisional cascading process, the so called Kessler Syndrome, named after D. J. Kessler (1978).

In order to better understand this problem and facilitate possible future policy discussions, we have decided to build a model based on aggregate values of existing models and datasets to predict the numbers of space debris grouped into four groups – inactive satellites, large debris (larger than 10 cm), medium debris (between 1 and 10 cm) and small debris (smaller than 1 cm). This categorization is consistent with the one used by NASA, ESA, and other space agencies.

Model

There are basically two dominant groups of feedback loops in our model. The first group is reinforcing, meaning that the more debris there is in the space, the more collisions will occur, creating even more debris (see Figure 1). The secondary group is balancing the reinforcing loops for bigger objects and strengthening the loops for smaller objects meaning that the collision will usually destroy some bigger object creating a cloud of smaller ones.

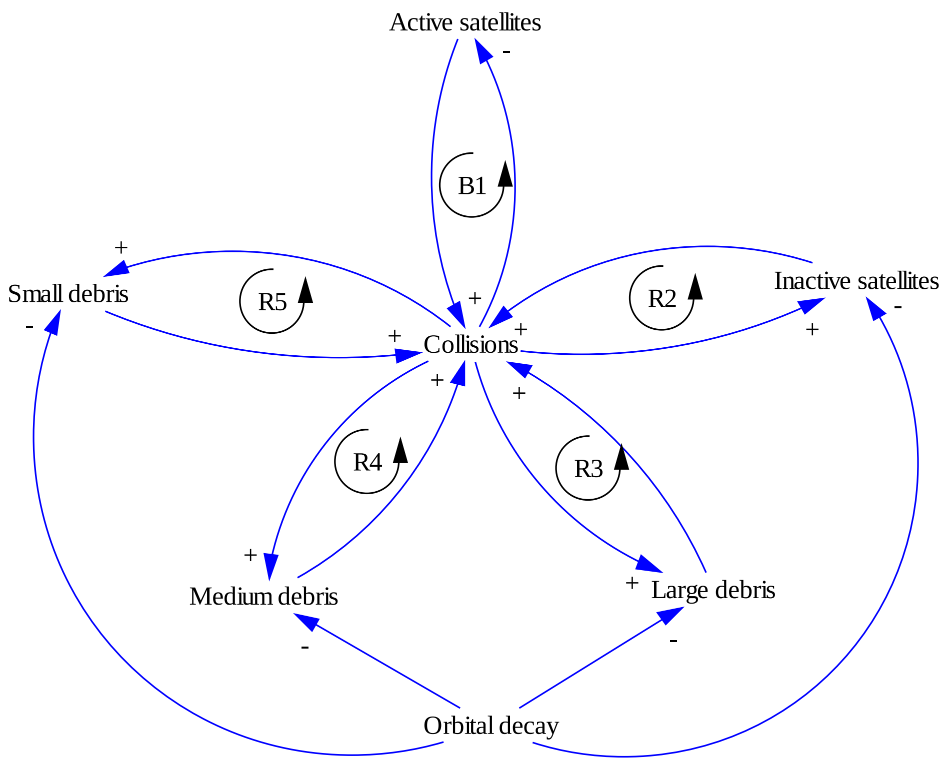

Fig. 1 - Simplified Causal Loop Diagram

We also assume that in order to fragment an object the collision must consist of objects of similar size. It practice, this means that a satellite can be fragmented only by another satellite or large object, a large object can be fragmented only by another large or medium object and a medium object can be fragmented by a medium or small object. Collision of an active satellite and medium object will disable the satellite making it an inactive satellite that is not operating anymore and loses its ability to maneuver. The collision of small debris and a satellite usually does not cause any harm as satellites are equipped with a shielding protecting them against these small fragments. We are also not modeling collisions of two active satellites as their positions are known precisely, their trajectories plotted ahead of time, both can maneuver, and the evasion success rate is so high that such a collision has never occurred so far.

Besides these spontaneous collisions we are also modeling a certain satellite malfunction rate and an effect of anti-satellite weapons. Both effects are simulated as exogenous factors with parameters estimated based on real-world data. The model also includes variable solar activity (11-year cycle) and its impact on decay times, as it heats up the atmosphere and increases drag on orbiting objects.

The probabilities and rate of collisions of objects from different groups were calculated using a conversion coefficient converting the rate of collisions between objects from one group to the rate of collisions between objects from another group. The initial rate was estimated using repetitive simulations and comparison of the resulting runs with real data.

Modeled scenarios and preliminary results

Our baseline scenario is best described as “business as usual”, where we simply extrapolate ongoing trends into the future. Running it for full 50 years (2016-2066) yields the expected result of perpetually growing amount of debris in the LEO. We can observe a nearly than 3-fold increase in the large debris (over 10 cm) and a 10-fold increase in medium debris (1-10 cm) quantities (Figure 2). Perhaps surprisingly, even such a dramatic increase in numbers still does not result in full realization of the Kessler Syndrome as most of the satellites being launched remain intact for their full lifetime. However, it comes with a significant increase in risk to satellites which is manifested by their higher yearly losses, making satellites operations riskier and more expensive for governments and private companies alike.

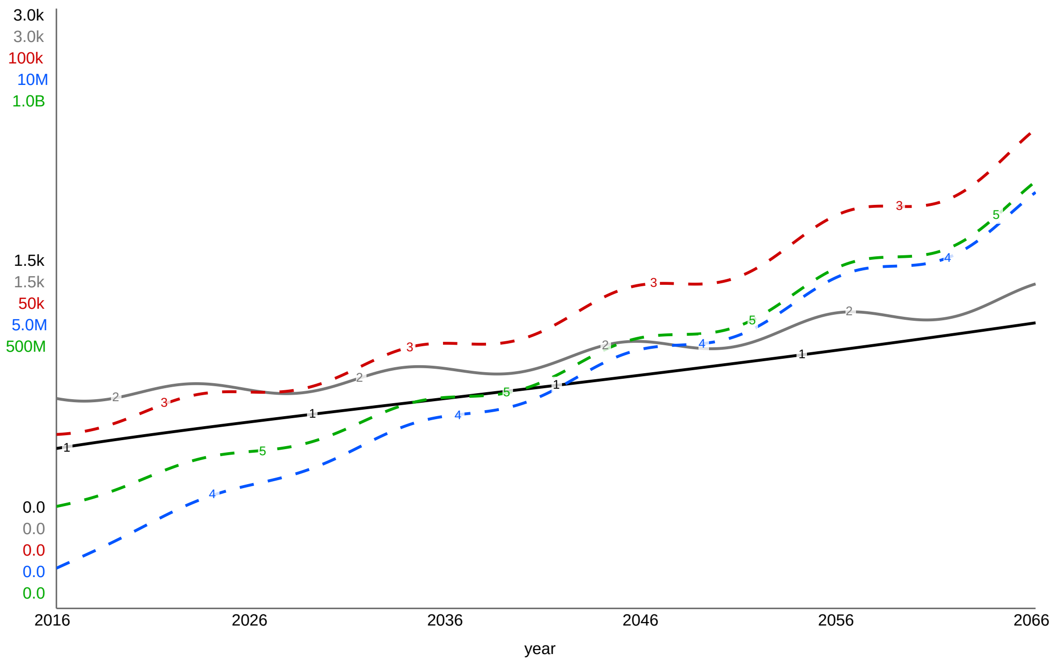

Fig. 2 - Satellites and debris during "business as usual" run

In our second scenario, we imagine some major military conflict erupting in the year 2040, during which roughly half of all military satellites is destroyed by intentional kinetic impacts using Anti-Satellite weapons (ASATs). With military and dual-use satellites generally representing a little over one third of all satellites (depending on the operating country), this equals to some 200 satellites destroyed by ASATs in 2040 (Figure 3). But even this event is not enough to trigger a chain reaction of satellites disintegrating in LEO, at least according to our model. Nevertheless, the number of collisions with active satellites ends up nearly twice as high at the end of the simulation (i.e. 25 years after the conflict and ASAT strikes) when compared to the previous run. This shows that the damage would be long-term and would negatively impact satellite operations (including commercial and scientific ones) for many years after any conflict nvolving ASATs.

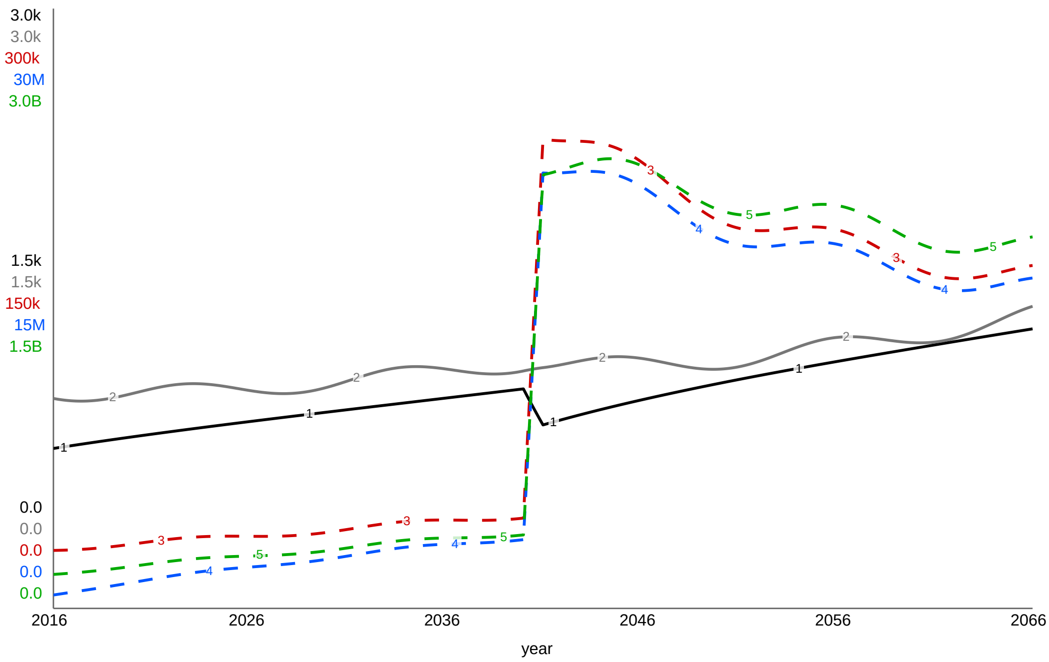

Fig. 3 - Satellites and debris during run with assumed conflict

Next, we ran the model without any launches after year 2040 (Figure 4). This serves to demonstrate the high inertia of the system. Counterintuitively, even with no satellites being launched, the amount of debris in LEO keeps growing for at least another 5 years. Only another 10 years later the orbital decay removes enough debris from LEO to return the total amount back to what it was in 2040 (but still much higher than what it was in the very beginning). This is caused mostly by the ongoing disintegration of already launched and inactive satellites, which essentially serve as reservoirs of future debris, ready to be scattered.

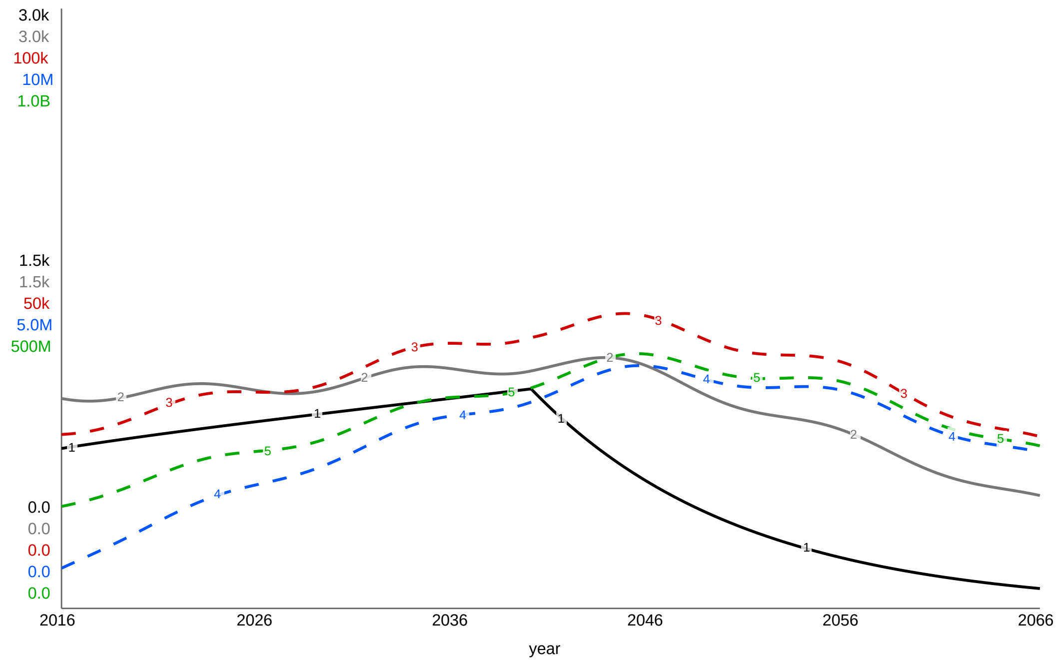

Fig. 4 - Satellites and debris with no launches after year 2040

Our fourth scenario represents an attempt to mitigate the situation and somehow “fix” the debris accumulation problem. We model this by removing some inactive satellites from the LEO (again, starting from 2040) before they get fragmented. We do not detail or discuss any specific method of possible debris mitigation, we simply deorbit the satellites “somwhow”. We find that removing 8 inactive satellites per month would stabilize the debris populations (Figure 5).

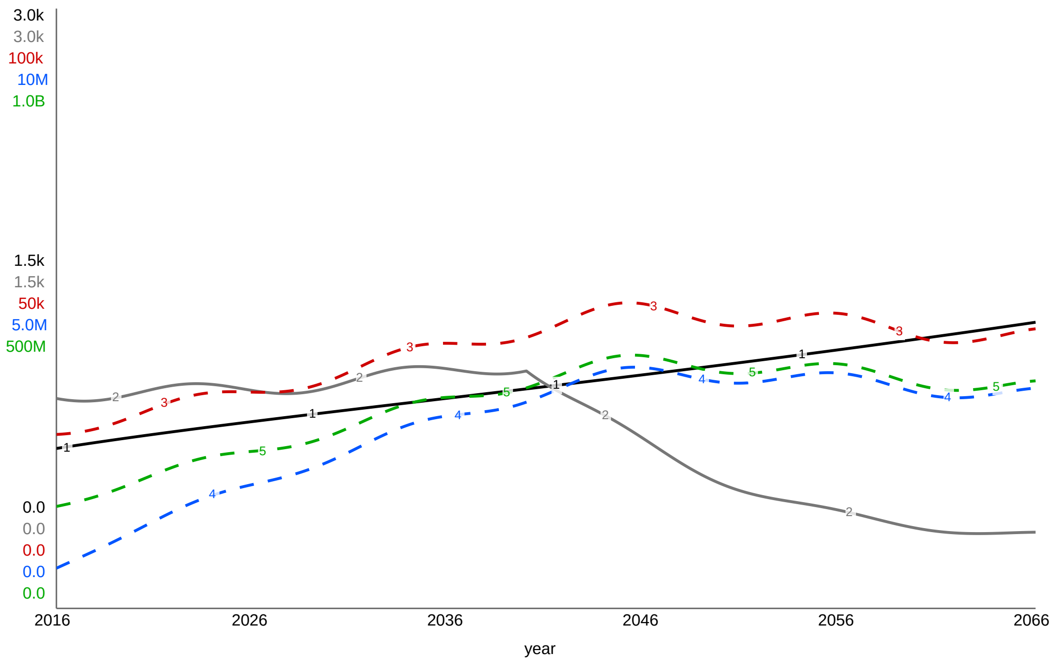

Fig. 5 – Debris mitigation policy

Our fifth and final scenario (Figure 6) is one modeling an EMP going off, leading to loss of control over satellites en masse. To model this, we turn one third of active satellites into inactive ones over a period of one year. This is notably less catastrophic (from the debris point of view) than using ASATs.

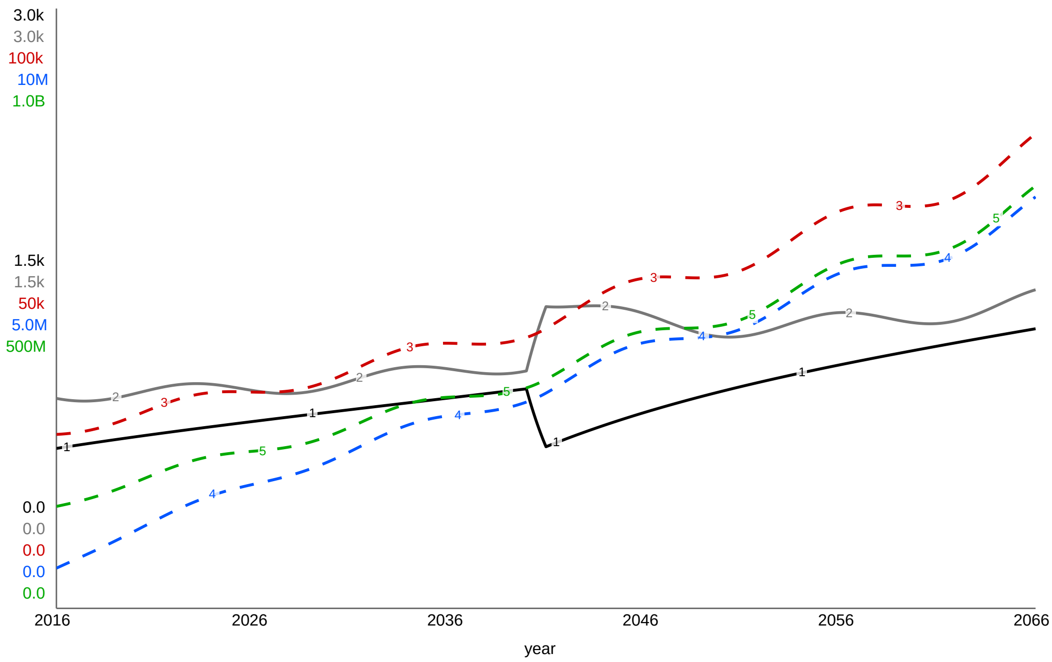

Fig. 6 – Satellite loss due to EMP

Conclusion

The results show that we are not as close to a catastrophic chain-reaction in LEO as it might seem. At the same time, the trend is quite clear. And we are not only approaching the catastrophic cascade at an accelerating rate (despite not being quite there yet), we are also making our existing and future space operations less safe and more expensive. Simply put, large amounts of debris make losses of equipment more likely. It is also conceivable that orbital collisions with debris could endanger the life of people working in, or passing through, LEO. Orbital debris can damage critical systems on space stations, weaken heat shields on spacecrafts, and even small pieces can hit astronauts during spacewalk.

Today, losses of satellites due to collisions are rather rare, but they might become quite common within a couple of decades, unless we change how we operate in LEO. Possibly even more alarming is the long-term effect of debris accumulation. Its great inertia means we need some sort of solution sooner rather than later, lest we harm our own future, when we will most likely be even more dependent on satellites and space technology than we are now.

Despite its high level of abstraction, this work demonstrates that System Dynamics is a viable approach to modeling the Kessler Syndrome and the associated issues of accumulation of orbital debris and the threat this poses to our satellites. Compared to other models, using different methods, it is probably more accessible and comprehensible to academics and practitioners from other, less technical fields, as well as to involved policymakers. Furthermore, it can be readily modified to include specific critical events (such as wars), changes in solar activity, rate of space launches, new industries and possible future debris mitigation attempts designed to either slow down its accumulation or even to remove certain fraction of the debris by somehow deorbiting it.

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