Julia Hudson[1]

[1]New Trier High School

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KESSYM: A stochastic orbital debris model for evaluation of Kessler Syndrome risks and mitigations

JULIA HUDSON

New Trier High School, 385 Winnetka Avenue
Winnetka, Illinois 60093, USA
julia.hudson@outlook.com

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Abstract -- Mankind's productive use of the low Earth orbit (LEO), from 400-2,000km in altitude, is at risk from increasing counts of debris objects and derelict satellites, which pose collision risks to active spacecraft. Of particular concern to space agencies and industry is the Kessler Syndrome (KS), which is the term for a hypothetical collapse scenario in which collisions between debris and satellites cause more debris, causing a destructive cascade that leaves the orbital environment unusable. In order to better understand this KS tipping point, the KESSYM model has been developed as a stochastic simulation of all the objects in the LEO. This model provides a forecast for the evolution of the orbital environment into the future, including the expected year, if any, that the KS collapse occurs. KESSYM allows for certain risks, such as war or terrorism in space, solar flares, or unconstrained exploitation of the space resources to be analyzed alongside KS mitigation measures, such as the hardening of spacecraft against debris, avoidance of collisions, removal of debris, and effective regulation. The conclusions drawn from the KESSYM simulation are that the KS is almost an inevitability within 200-250 years of today's date, but can be delayed or avoided altogether if action is taken.

Keywords: space debris; Kessler Syndrome; low Earth orbit.

1. Introduction

The low Earth orbit environment (LEO) is currently populated by approximately 2,000 active satellites, providing essential communications, imaging, sensing, navigation, scientific, and military services to countries and agencies on earth. These spacecraft share the orbital environment with approximately 6,000 derelict satellites, as well as an estimated 1,000,000 fragments sized 1-50 cm, and 130,000,000 microfragments from 1 mm to 1 cm in size [European Space Agency (2022)]. With a typical orbital velocity of 28,000 km per hour, even a collision with a loose bolt or fleck of paint can be destructive, let alone a 100 kg fragment of a rocket. An average collision in the LEO would release on the order of 8×10^{10} joules of energy [Kessler (1995)]. Even with today's modest exploitation of space, collisions do occur regularly and are top of mind for mission planning.

There are parallels between pollution of the LEO and of other environments like the oceans or the atmosphere, but significant differences. Importantly, orbital debris is a long-lasting threat to other objects in orbit, and collisions can cause debris, which can then result in other collisions and more debris. Given these conditions, it is not difficult to imagine the scenario of a chain reaction of collisions, debris, and more collisions. As this chain reaction continues, eventually a tipping point is reached, and the LEO becomes a congested cloud of debris inhospitable to further use by manned or unmanned spacecraft. Space is Closed.

The researcher credited with first imagining this scenario was Donald Kessler, who co-authored a paper in 1978 titled, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt" [Kessler (1978)]. The risks highlighted by Kessler, namely that the concentrations of debris in orbit could intensity in cascading events, became known later as the "Kessler Syndrome." The idea gained traction, and others continued to study the problem in the decades to follow, with Kessler himself following up in 1991 with an additional paper: "Collisional cascading: The limits of population growth in low Earth orbit" [Kessler (1991)]. The essence of his analysis is on the rates of production of debris, and whether the rate of adding new debris is faster than the rate at which it decays from orbit. Unless these rates are kept in balance, the "debris belt" could be created and mankind's use of space will meet the "limits of population growth."

And even though these risks were first identified over forty years ago, the exploitation of the LEO has continued largely unfettered by national space agencies, military bodies, and increasingly, private companies. As one example, a single company, Elon Musk's SpaceX, has been licensed to deploy 42,000 satellites for its Starlink service [Massey (2020)]. Due to the long distances involved, the lack of territorial boundaries, and the multinational nature of space activities, any regulation or cooperation regarding littering the LEO is difficult to monitor or enforce. And with each year bringing record numbers of new launches, and the proliferation of giant satellite "constellations" such as Starlink, the threat of the KS coming to pass becomes less of an academic exercise and more of a dire threat. The future of mankind in space demands that the KS risks are understood.

In order to attempt to quantify and analyze these KS risks, I have developed KESSYM (KESsler SYndrome Model), which is a stochastic risk simulation of debris and spacecraft in the low Earth orbit. Using KESSYM, I will try to answer some questions about the Kessler Syndrome in this paper:

(i) *How exactly should we define the Kessler Syndrome?*
(ii) *What is the risk that the KS occurs? How does this risk change over time?*
(iii) *If the KS does occur, is it fast or slow? Is there any warning?*
(iv) *What events might increase the likelihood of the KS?*
(v) *What actions could be taken to reduce the likelihood of the KS? Which actions are likely to be most effective?*

Questions *(i)*-*(iii)* are critical to understand as trillions of dollars are invested in space over decades to come, and civilization on Earth becomes more dependent on services provided from the LEO. Question *(iv)* is important as stakeholders in space consider significant events which could prove disastrous for the orbital environment. What might happen if there were a war where anti-satellite weapons were deployed? An act of terrorism in the LEO? Or simply what if the rate of new satellite deployment far exceeds current estimates? And what of the ever-present and unpredictable risks of solar flares, which can wreak havoc on the electronic components of satellites?

In terms of actionable outcomes from this simulation, question *(v)* is perhaps the most important. What can and should be done? Ever since the understanding of the Kessler Syndrome began to emerge in 1978, stakeholders in the space environment have been dreaming up solutions and mitigations for the debris problem. These solutions can be generally categorized into a few buckets, which we will use for this analysis:

- **Hardening vs microfragments:** Implementation of design changes, materials, and redundancy to make spacecraft less susceptible to damage from small particles and debris in orbit
- **Fragmentation prevention:** Policies, procedures, regulations to reduce fragments created during launches, accidents, spontaneous explosions, and from deterioration over time
- **Collision prevention:** Systems to predict collisions based on detection of threatening objects, and protocols and procedures for craft to navigate out of danger
- **Population management:** Policies, procedures, regulations to remove satellites from orbit after their useful life, reducing the population of derelict satellites
- **Active debris removal:** Missions are launched, or technologies employed with the purpose of removing fragments from the LEO. Various strategies have been suggested for this approaching ranging from nets to magnets to automated drones.
- **Launch moratorium:** If the LEO environment is showing signs of collapse, then a 1-year worldwide moratorium on new launches is put in place. This allows for the environment to recover through natural decay of fragments and de-orbiting of end-of-life satellites. This would be considered a strategy of last resort, as a launch moratorium would be detrimental to the unmanned, and especially manned, use of space.

The measures prescribed here, except for the launch moratorium, were compiled from the literature on orbital debris management, including [Brettle *et al.* (2021)], [Lewis (2020a)], [Reiland *et al.* (2021)]. The launch moratorium has not been considered previously, at least in my review of the research, but is included for academic interest. The simulation developed here with the KESSYM model allows for exploration of these modes of mitigation to determine which the most effective for keeping space open.

2. Methods

The KESSYM model was developed to be a comprehensive rapid stochastic simulation model of the entire LEO environment. It includes a population model, tracking increases and decreases over time in the number of active and derelict spacecraft, and debris of different sizes. KESSYM also includes a collision risk and outcome model, using the cross-section and density characteristics of the objects in orbit to forecast the likelihood in any given time period of collisions between the objects, and the impact of those collisions in terms of new debris formation. Finally, the model includes a scenario manager, which allows for the results to be sensitized around the impacts of additional risk parameters such as war and solar flares, and also the effects of mitigation measures such as hardening and orbital management.

KESSYM is intended to be a form of "meta-model" bringing together best practices and assumptions from prior work into a stochastic risk simulation that provides insight into the problem and actionable advice on solutions. The model is designed to deliver statistical expectations of outcomes, as opposed to an empirical engineering simulation. Orbital mechanics and collisions are modeled on a probabilistic basis based on a "density" of objects in the LEO, rather than by tracking exact flight paths. The techniques of Monte Carlo simulation are employed to evolve the model forward in increments of time for a century or more, which is an approach used in other efforts to model the LEO [Lewis (2020b)], [Liou (2006)]. The use of this stochastic risk model provides a good means to describe the likelihood of the KS tipping point, when cascades of debris occur faster than they are mitigated. The output of the simulation is the condition and population of objects at various date mileposts, and the determination whether the KS has occurred or not.

2.1. *Stochastic Risk Model*

The KESSYM model is built in Microsoft Excel and employs the Palisade @Risk engine for stochastic risk simulation. @Risk is one of the premier commercial risk simulation software programs, used widely in industries such as insurance, construction, and finance. The KESSYM model is flexible in terms of time evolution, with a granularity between 1 and 12 months per time cycle, and an intended horizon of 50-600 years in the future. For the figures in this paper, runs of 300 years were simulated with a quarterly cycle frequency (3 months per cycle), meaning that a total of 1,200 time periods were modeled.

Probability distributions such as Normal and Pearson are used to model events with a range of outcomes, such as how many fragments are created by a given collision. Binomial and Poisson distributions are used to model the number of events based on probabilities, such as the number of satellite-fragment collisions that occur in a given time period. The Mersenne Twister algorithm was used for seed generation to ensure appropriate randomness. Good convergence of results was usually achieved with about 1,000 simulation runs, but to ensure quality results for this paper the results were based on 5,000 runs.

In summary, the KESSYM model has been designed as an abstracted, results-oriented, rapid-analysis scenario debris and collision simulation model for the LEO. Due to this flexibility, tens of thousands of simulations can be run in the course of a few hours, and statistical insight to the model sensitivities can be gained rapidly.

2.2. *Population Model*

The KESSYM model maintains a running population model of three categories of objects in the LEO: microfragments, fragments, and satellites. This is fewer distinct categories than have been previously modeled in other simulations, which might have seven or more bins [Diserens (2022)]. The reason for this is as mentioned earlier: the KESSYM model is abstracted and results-based, and the minimum number of categories are used needed to deliver meaningful results. The functional difference for debris objects is their ability to cause damage in a collision and whether or not the object can be tracked from Earth, as seen here:

Table 1. Categories of orbital objects in the Population Model.

Object	Microfragment	Fragment	Satellite
Mass	<1 kg	>1 kg; <500 kg	> 500 kg[b]
Size	<1 cm	>1 cm; < 0.5 m	> 0.5 M
Visibility	Not tracked	Can be tracked[a]	Tracked easily
Collision with satellite	May disable	Likely to disable or destroy	Catastrophic
Population (2022)	130,000,000	1,000,000	10,000

[a]Model maintains a percentage of fragments that can be tracked, which increases over time in some scenarios

[b]Model assumes that satellites get smaller on average over time, so in future time periods satellite are likely to be less than 500 kg

For this model's purpose, microfragments are intended to represent a category of object that is too small to ever be tracked or detected reliably, but that could still damage a spacecraft. Examples would be flecks of paint, remnants of unburnt solid fuel, and small screws. Fragments are intended to describe everything larger than a microfragment and smaller than a satellite, which either now or in a future decade can be tracked from Earth or space. These objects will likely damage or destroy a satellite in a collision. Examples would be pieces of a rocket which has exploded, fragments from two satellite colliding, or shards resulting from the breakup of a derelict satellite. The altitude of individual objects with the LEO range of 400 to 2,000 km is not maintained in the simulation, under the assumption that the added complexity to model this granularity would not provide sufficient additional insight. Fragments and microfragments are assumed to have an average lifespan of 200 years in orbit, intended as an aggregate of typical lifespans for these objects, which range from decades in the lower part of the LEO to millennia in the highest section [Rossi *et al.*].

Satellites are the most critical form of population in the LEO, as these represent the tools for utilizing the space resource. The model does not distinguish between different sizes of satellites or functions, but aggregate characteristics of the satellite fleet are maintained in the model, such as average age and average mass. The KESSYM model also tracks the population of satellites which are "active," as in operating according to purpose, or "derelict" and no longer active. A satellite might become a derelict either by design at the end of its useful life, due to an accident, or as the result of a collision with fragments or microfragments. Uncontrolled derelict satellites are assumed to have an average lifespan of 100 years in orbit, which is lower than that of fragments due to generally lower orbits and higher atmospheric drag. Satellites which reach the end of their useful life are assumed to be de-orbited within 20 years on average.

During every time sequence evolution for the model, the populations of microfragments, fragments, and satellites are adjusted. New launches increase the satellite population, while collisions and decommissionings will reduce it. Collisions and explosions increase the population of microfragments and fragments, while the natural decay from orbit reduces satellite and debris populations.

2.3. *Collision Model*

A key driver of model outcomes is the estimation for the number of collisions occurring between objects in the LEO. The types of collisions considered were: satellite-satellite (which could include either active or derelict satellites), satellite-fragment, and satellite-microfragment.

A survey of the literature shows that collision probability models for the LEO range from detailed engineering simulations to abstracted density models, and hybrids in between. The engineering models go as far as to track the altitude, apogee, and eccentricity of each object and its intersection with other tracked objects [Sdunnus *et al.* (2004)]. These models would hopefully be able to provide a good degree of accuracy, but require vast computational power to simulate scenarios far into the future, because as the number objects increases, the requirement to track interactions increases exponentially.

Other models for collision probability begin with an ideal gas model as a core, that is, assuming that the objects in the LEO will have similar characteristics to particles in a gas (though without the concept of container walls) [Bradley (2009)]. In this case, the probability of a collision Z_{ab} between two particles a and b in a given time period is proportional to the density of the two gases, N_a/V and N_b/V, the cross-sectional area of the molecules, πd^2_{ab}, and the magnitude of their combined velocities v_a and v_b:

$$Z_{ab} = \frac{\pi d^2{}_{ab}\sqrt{\left(\langle v_a\rangle^2 + \langle v_b\rangle^2\right)}\, N_a N_b}{V^2} \tag{1}$$

Some models in use form a type of hybrid to these two approaches, modeling collisions abstractly, but trying to simulate certain orbital characteristics at the same time [Boley and Byers (2021)].

For purposes of KESSYM, given that the model is intended for rapid results and also that the simulation is intended to extend hundreds of years into the future where it is unknown exactly how space operations will be conducted, I have decided that the ideal gas based approach will provide a good compromise between accuracy and usability. Because the velocity of all objects in the LEO is relatively similar, the collision probability Z_{ab} based on the ideal gas formula can be simplified to:

$$Z_{ab} = C_0 \times A_s \times D_a \times D_b \tag{2}$$

A_s is a factor for the combined area of the two objects a and b, and D_a and D_b are the relative density of the objects in space. The parameter C_0, which combines the cross-section and velocity, is a constant and was tuned to try and match the historical data set for the number of collisions which have occurred.

An important further addition to the collisions model is a concept of avoided collisions. It is the current practice in space operations to track known satellites and fragments, and to notify operators regarding impending collisions and try to avoid them the extent possible, usually through slight changes in the orbit [US Space Command (2022)]. Given that only a small percentage of the fragments can currently be monitored and that not all satellites can be controlled, the probability for being able to avoid collisions involving an active satellites and a fragment is assumed to be 5%, while an active satellite has a 50% of avoiding a collision with another satellite[*]. In one of the sensitivity scenarios, this percentage increases over time, as it assumed that a greater percentage of the fragments will be able to be tracked, and evasion protocols improved.

2.4. *Input Parameters*

The key parameters for the KESSYM model were tuned to try and provide a good match with the historical data set in terms of what has happened in the LEO for the past three decades, and also with work done by the space agencies such as NASA and ESA. Examples of the parameters that were fit: the frequency of launches of new satellites, the likelihood of avoiding collisions among tracked objects, the rate of orbital decay for uncontrolled objects, the impacts of collisions in terms of fragments created, and the probability of collisions based on object densities. For these parameters, the KESSYM model relies on prior work in the space debris field from efforts at NASA and the ESA, and academic researchers [Horstmann *et al.*].

KESSYM also maintains parameters to model the future use of space. There is no way to determine with any certainty what the rate of rocket launches will be 100 years from now, how many satellites will be deployed in the LEO, and how effective future measures to reduce collision risk will be. I have tried to provide a base case set of assumptions that

[*] Currently over 30,000 debris objects are actively tracked, out of an estimated population of 1,000,000 fragment-size objects. The quotient of these two numbers is rounded up to 5% to assume more objects are tracked in the future, and other means of avoiding collisions developed.

extrapolate current growth in space exploitation to future periods, informed by literature on this topic. The general assumptions for my base case are that the rate of adding spacecraft to orbit by nations and companies steadily increases, satellites generally become smaller and more numerous, and that mitigations measures to decrease debris and collision frequency are put in place. On top of this base case, I then introduce the sensitivity scenarios, including catastrophic events such as war in space, and mitigations such as increased regulation.

Because KESSYM is a stochastic simulation, many parameters are input along with a probability distribution. For example, the number of debris fragments created from a satellite collision is modeled as a normal distribution with an average of 10,000, with 90% of the outcomes being between 4,500 and 15,500 fragments. The distributions were chosen to try and provide a good fit with the literature when available. For example, in the case of on-orbit satellite fragmentations, the parameters were tuned to try and match the outcomes of the historical data set [Anz-Meador (2018)].

The parameters values used in the model, along with the distributions assumptions, are summarized in Appendix A.

2.5. *The Kessler Syndrome (KS)*

As most of the key outputs sought from the KESSYM model have to do with the risks of the KS occurring and how to manage those risks, it is essential to first develop a working definition for the KS, as was asked in the first question of the introduction:

(i) How exactly should we define the Kessler Syndrome?

As indicated, the accumulation of debris in the LEO is a cascading effect, where debris causes collisions, generating more debris and repeating the cycle. The KS occurs when the rate of new debris generation overwhelms the rate at which debris natural decays or is actively removed, and the environment becomes hazardous to ongoing operations. There does not appear to be a consensus quantitative definition in the literature as to exactly when the KS has occurred. We can suggest a number of definitions in this paper which attempt reasonably to describe a discrete point at which the LEO is essentially unusable, where further launches of spacecraft are uneconomic due to debris hazards:

a) **Lifespan Threshold.** The expected lifespan of satellites in orbit falls below 67% of their intended design life due to damage or destruction from debris. For example, if satellites are supposed to have an operational life of 30 years, and if due to collisions the average lifespan goes below 20 years, then the Kessler Syndrome is in effect.

b) **Replacement Threshold.** The KESSYM model assumes that when useful satellites are destroyed, a certain number of replacements will be launched to maintain the functions. The KS will be in effect if the average number of replacement satellites reaches 25% of the number of new satellites launched. For example, if 1,000 new satellites are expected to be launched in a future year, and at in the same year 250 or more additional replacement satellites are needed, then the Kessler Syndrome has transpired.

c) **Collision Probability Threshold.** The risk of a collision between an active satellite and another satellite or fragment exceeds a reasonable threshold, such as 1% per year. This is assumed to be level at which point investing in future satellites would be uneconomic, given that they would have a high likelihood of not surviving for their intended design life.

In each definition, if the metric exceeds the threshold in any of the simulation years, then that date is recorded as the KS onset. For purposes of evaluating risks and strategies, an average of the three KS definitions was used to define the KS onset date.

3. Conclusions

The following outputs from the KESSYM model are based on 5,000 runs for each scenario (combination of input parameters), where each run is a 300-year simulation of the LEO at 3-month intervals. Thus, there are 1,200 time periods simulated in each run, which provides for a reasonable compromise between model granularity and accuracy and computational time to run the simulations. Each of the questions posed in the Introduction was answered with the model outputs.

(ii) What is the risk that the Kessler Syndrome (KS) comes to pass? How does this risk change over time?

The simulation was run tracking the three metrics being used to mark the onset of the KS. Based on these definitions, the following results are seen in the base case scenario:

Table 2. Time horizon for expected Kessler Syndrome onset.

Kessler Syndrome threshold	Years Elapsed[a]	P5 / P95[b]	Likelihood within 100 years	Likelihood within 250 years
Lifespan <67% of design	253	233 / 268	0.03%	32%
Replacement >25% of new	252	216 / 278	0.11%	38%
Collision Probability >1% per year	223	205 / 237	0.03%	100%
AVERAGE	**243**	**222 / 258**	**0.03%**	**71%**

[a] The number of years elapsed after the beginning date of the simulation, which is January 1, 2023.

[b] The 5th percentile case and the 95th percentile case, meaning that 90% of the expected outcomes will be between the P5 and the P95 values.

Figure 1 provides a histogram of the simulation results for the AVERAGE row:

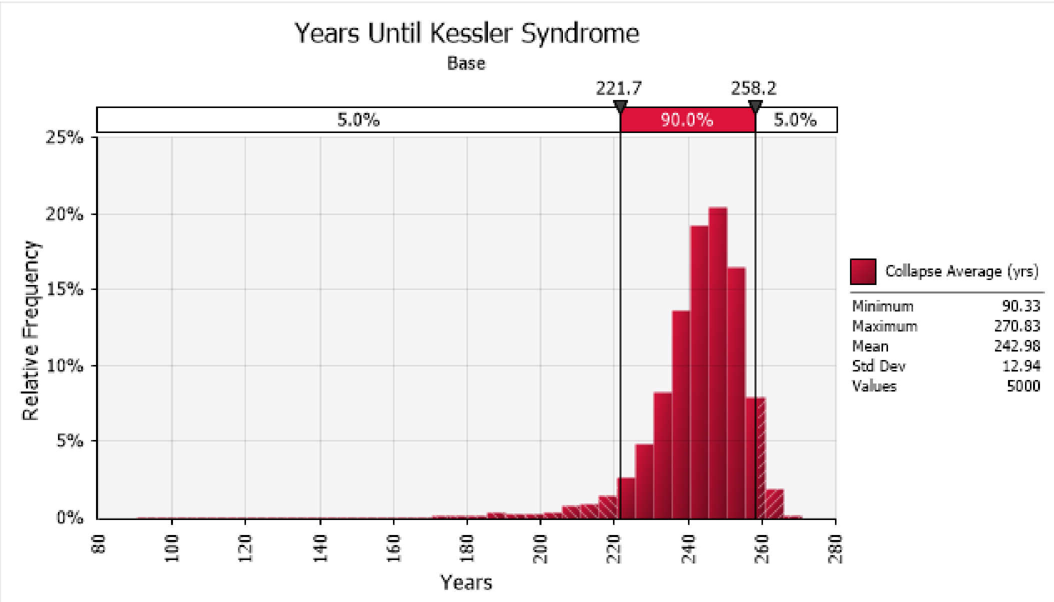

Fig. 1. Results of 5,000 300-year simulations, plotting relative frequency of collapse year based on the average of the three KS definitions. Note P5/P95 values of 222/258 years, as well as simulation low/high of 90/271.

The base case scenario thus predicts the collapse of the usable LEO environment is likely within a range of 222-258 years from today's date, if no additional mitigations are taken and the use of space increases according to current trends. Or looking at it another way, the KESSYM model predicts approximately 1 in 3,300 chance of the KS onset within 100 years, but a 71% likelihood within 250 years.

(iii) If the KS does occur, is it fast or slow?

To answer this question, we will use the same definitions of the Kessler Syndrome onset as before, but set the threshold of 50% of the original metrics. We can then look at how this changes the year that the syndrome is realized and give a determination for the speed of onset.

Table 3. Expected warning period for Kessler Syndrome onset.

Kessler Syndrome warning threshold	Years of warning provided	P5 / P95
Lifespan <83% of design	35	21 / 50
Replacement >12.5% of new	27	21 / 50
Collision Likelihood >0.5% per year	30	17 / 43
AVERAGE	**31**	**18 / 44**

The KESSYM model shows that the KS is not likely to happen suddenly on the order of days or months; it is expected that humanity will have a few decades of warning in which to take corrective action, estimated at 18-44 years.

(iv) What events might increase the likelihood of the KS?

A few scenarios are considered here which might cause disruptions to the space environment. In the War scenario, we assume that conflicts on the surface will sometimes escalate into space. In any given year, it is assumed there is a 0.5% chance of a war impact. In the Terrorism scenario, we assume that non-state actors will periodically destroy satellites through sabotage or weaponry, or alternately that state military functions destroy their own craft to test anti-satellite weapons, with a frequency of 1% in any given year. In the Solar Flares scenario, we assume that the sun enters an active cycle, and that there is a 1% chance in any given year that a solar flare will disable a significant fraction of the satellite fleet. In the Constellations scenario, we assume that the trend towards more and smaller satellites is vastly accelerated. The More Rockets and Fewer Rockets scenarios are intended to provide data regarding the sensitivity of the KS onset to the overall pace of space exploitation.

Table 4. Impact of adverse effects to Kessler Syndrome onset.

Event	Impact	Change to KS Onset[a]
War, per event	1-1000 satellites destroyed	-9 years
Terrorism or weapon test	1-20 satellites destroyed	-1 month
Solar Flares	1-10% of the satellite fleet disabled	-9 years
Constellations	Number of satellites per rocket increases at 2x the base case rate	-36 years
More Rockets	2x higher rate of rocket launch increases over time	-54 years
Fewer Rockets	Half the rate of rocket launch increases over time	+42 years

[a]The number of years expected that the event measure would (-) hasten or (+) delay the KS onset

The simulation results show that discrete events can have a material impact on the KS onset, with the solar flare and war events equally disruptive. However, even more significant to the KS onset date are changes to the rate of adding additional spacecraft to the LEO, either through more rocket launches, or the use of more, smaller, satellites.

(v) What actions could be taken to reduce the likelihood of the KS? Which actions are likely to be most effective?

The KESSYM model allows for rapid simulation of various mitigation strategies. These strategies were added to the base model case one at a time, so that the individual impacts could be quantified, and then an “All of the Above” scenario was run which assumed that all mitigants were in place. Note that for All of the Above and Launch Moratorium, the KS date determined was outside of the bounds of the original 300-year run, so an additional 5,000 runs were done with a 600-year time horizon (using 6-month intervals). In all cases, the mitigants were assumed to begin 10 years after the simulation start date of January 1, 2023. As can be seen, the efficacy of these strategies varies significantly:

Table 5. Impact of mitigation measures to Kessler Syndrome onset.

Mitigation measure	Degree of mitigation	Change to KS Onset[a]
Hardening vs microfragments	-1% per year of damage from microfragment collisions	+17 years
Fragmentation prevention	-1% per year fewer fragments and microfragments created from breakups and explosions	+14 years
Collision avoidance	-1% per year collision likelihood from satellite-satellite or satellite-fragment collisions	+39 years
Population management	1% per year increase in the number of derelict satellites de-orbited	+172 years
Active debris removal	10,000 objects removed per year, increasing by 1% per year	+5 years
All of the Above	Above degree of all mitigations	Indefinitely[b]
Launch moratorium	All satellite launches halted for 1 year after each KS warning (ongoing)	+115 years

[a]The number of years expected that the mitigation measure would (+) delay the KS onset.
[b]Employing all of the mitigation measures simultaneously delayed the KS beyond the simulation 600-year time horizon.

The most effective strategies appear to be Collision Avoidance and Population Management, both of which lower the incidence of catastrophic collisions involving satellites, thus abating massive sources of new debris. All of the mitigation approaches help to delay the onset of the KS, and when used in combination, can effectively defer the KS from ever occurring.

4. Discussion

The KESSYM model ominously predicts that current use of space is not sustainable. Without changes to the way in which space operations are performed, it is simply a question of time before the LEO becomes choked with debris. This does not appear to be an imminent problem: the KESSYM model predicts on average 243 years for the onset of the KS, though there is a 0.03% chance it could be as soon as 100 years from now.

Destructive events in the LEO such as war, terrorism, are expected to have some impact on the KS onset, with these events advancing the KS forward by 0-9 years. The most important factor is the rate of launching new satellites and rockets, where increasing launch rates move the KS onset ahead 36-54 years.

Fortunately, there are a number of strategies which could be adopted to manage the LEO, including hardening the spacecraft, preventing fragmentation, detecting and avoiding collisions, and actively de-orbiting defunct satellites. As a last resort, the space agencies of the world could consider a moratorium on new launches whenever the KS seemed to be imminent. These strategies singly are expected to be effective individually in delaying the KS by 5-172 years, and together can defer the syndrome indefinitely.

This Space is Closed scenario is one possible future that awaits mankind if we do not manage the space environment, which can be considered as similar to other “commons” which humanity is tasked with managing. Commons are resources which are used jointly, such as the oceans, the Arctic, the atmosphere, the radio frequency spectrum, the Internet, to name a few. All of these commons resources are subject to pollution and depletion from over-use. The economist William Forster Lloyd is credited with originating a concept that became known as the “tragedy of the commons,” which describes how uncoordinated and unregulated use of common resources is likely to lead to their collapse [Lloyd (1832)]. The solution to this tragedy is for the stakeholders to apply coordination and regulation to their shared use, and create a system of order that provides for a sustainable future.

For humanity to enjoy the boon of space--improved communication, imaging, information, intelligence, science, and exploration--requires international cooperation and sound long-term policymaking.

5. Acknowledgments

I thank my parents for taking me to the Smithsonian Air and Space Museum when I was in middle school, where enthralling exhibits on the orbital environment stirred my curiosity (and alarm).

Appendix A. Simulation Inputs

All input parameters not described elsewhere in the paper are included in Table A.1. Estimates for many parameters are informed by literature as noted, while others represent a best-efforts estimate by the author. Further research will be required to tune these paraments to increase the accuracy of the KESSYM model.

Table A.1. Simulation Inputs

INPUTS	Units	Simulation Value (P5 / P95)	Distribution (if any)	Notes / Source
Model start date	*date*	1/1/2023		Current-year basis
Starting active satellite population	*count*	2,000		[ESA (2022)]
Starting derelict satellite population	*count*	6,000		[ESA (2022)]
Satellite average lifespan	*years*	15		Estimate based on historical [Anz-Meador et al. (2018)]
Average age of starting satellite population	*years*	7.5		Assume current fleet at half of lifespan
Average mass of starting satellite population	*kg*	4,000		[ESA (2022)]
Rocket launches per year	*count*	120 (54 / 186)	*normal*	Starting point from [ESA (2022)]
Linear increase in launches per year	*count*	10		Estimate of future trends [Diserens (2022)]
Satellites per rocket	*count*	2 (1 / 19)	*f*	Estimate based on historical and current constellation trends
Increase in satellites per rocket per year	*percentage*	1.5% (1% / 2%)	*normal*	Estimate based on current constellation trends
Average payload mass per rocket initial	*kg*	4,000 (1,807 / 6,193)	*normal*	[ESA (2022)]
Payload mass per rocket, yearly increase	*%/year*	0.50% (0.1% / 0.9%)	*normal*	Estimate based on current trends
Replacement launches for satellites lost	*percentage*	50%		Estimate based on expected need to replace satellite functions
Time delay for replacement launches	*months*	24		Estimate of time to prepare and launch new mission
Satellite decay rate (derelict controlled)	*%/year*	5%	*Poisson*	Derelict satellites de-orbited within 20 years [Liou and Johnson (2006)]
Satellite decay rate (derelict uncontrolled)	*%/year*	1%	*Poisson*	Natural decay of 100 years

INPUTS	Units	Simulation Value (P5 / P95)	Distribution (if any)	Notes / Source
Likelihood of a disabled satellite remaining controlled	*%*	25%		Estimate
Loss of control of derelict satellites	*%/year*	1.00% (0.5% / 1.5%)	*normal*	Estimate of yearly attrition
Starting fragment population	*count*	1,000,000		[ESA (2022)]
Risk of explosion per satellite	*percentage*	0.001% (0% / 0.003%)	*normal*	Estimate from historical [Anz-Meador et al. (2018)]
Fragments per launch	*Count/launch*	10 (2 / 46)	*Pearson*	[Diserens (2022)]
Fragments from operations	*count/ satellite/yr*	0.1 (0.01 / 0.6)	*Pareto2*	[Diserens (2022)]
Fragments per explosion	*count*	5,000 (888 / 9,112)	*normal*	Estimate from collision [Kessler (1978)]
Fragments per sat-sat collision	*count*	10,000 (4,517 / 15,483)	*normal*	Estimate from collision model [Kessler (1978)]
Fragments from fragment-sat destruction	*count*	2,000 (903 / 3,097)	*normal*	Estimate from collision model [Kessler (1978)]
Fragments from microfragment-sat collisions	*count*	0.0100	*normal*	Estimate from collision model[Kessler (1978)]
Fragment decay rate	*%/year*	0.50%	*normal*	Estimate from decay model [Lewis (2020b)]
Starting microfragment population	*count*	130,000,000		[ESA (2022)]
Microfragments per launch	*count/satellite*	200 (176 / 226)	*Pearson*	[Diserens (2022)]
Microfragments from operations	*count/ satellite/yr*	1 (0 / 6)	*Pareto2*	[Diserens (2022)]
Microfragments per explosion	*count*	200,000 (90,000 / 310,000)	*normal*	Estimate from collision model [Kessler (1978)]
Microfragments per sat-sat collision	*count*	1,000,000 (450,000 / 1,500,000)	*normal*	Estimate from collision model [Kessler (1978)]
Microfragments from fragment-sat collision	*count*	3,000 (1,350 / 4,650)	*normal*	Estimate from collision model [Kessler (1978)]
Microfragments from fragment-sat destruction	*count*	200,000 (90,000 / 310,000)	*normal*	Estimate from collision model [Kessler (1978)]
Microfragments from microfragment-sat collisions	*count*	0.50 (0 / 1)	*normal*	Estimate from collision model [Kessler (1978)]
Microfragment decay rate	*%/year*	0.5% (0.1% / 0.9%)	*normal*	Estimate from decay model [Lewis (2020b)]
Sat-sat velocity and cross-section constant C_0	*Count / Density² / m²*	30		Parameter fitted to historical data set and forecast [Liou and Johnson (2006)]

INPUTS	Units	Simulation Value (P5 / P95)	Distribution (if any)	Notes / Source
Likelihood of avoiding active satellite collision	*%*	50%		Estimate based on current operations [US Space Command (2022)]
Fragment-sat velocity and cross-section constant C_0	*Count / Density² / m²*	22.5		Parameter fitted to historical data set and forecast [Liou and Johnson (2006)]
Likelihood of avoiding active fragment-satellite collision	*%*	5%		Roughly only 5% of fragments can currently be tracked [US Space Command (2022)]
Likelihood of satellite disabled	*%*	60%		Fragments are large enough that a collision is likely to disable
Likelihood of satellite destruction	*%*	6%		Estimate that 10% of disabling events will result in destruction
Likelihood of destroyed satellite explosion	*%*	10%		Estimate based on historical record of likelihood of explosion vs breakup in orbit
Microfragment-sat velocity and cross-section constant C_0	*Count / Density² / m²*	15		Adjusted fragment cross-section parameter to account for smaller surface area
Likelihood of satellite disabled	*%*	1.0%		Most microfragments will cause superficial damage
Likelihood of satellite destruction	*%*	0.1%		Small probability of damaging critical system such as propulsion

Appendix B. Example Simulation Run

For illustrative purposes, I have included visualizations for the population model and also the three threshold definitions of Kessler Syndrome onset used in this paper: reduced satellite lifespan, excessive replacements needed, and collision probability.

B.1. *Population Model*

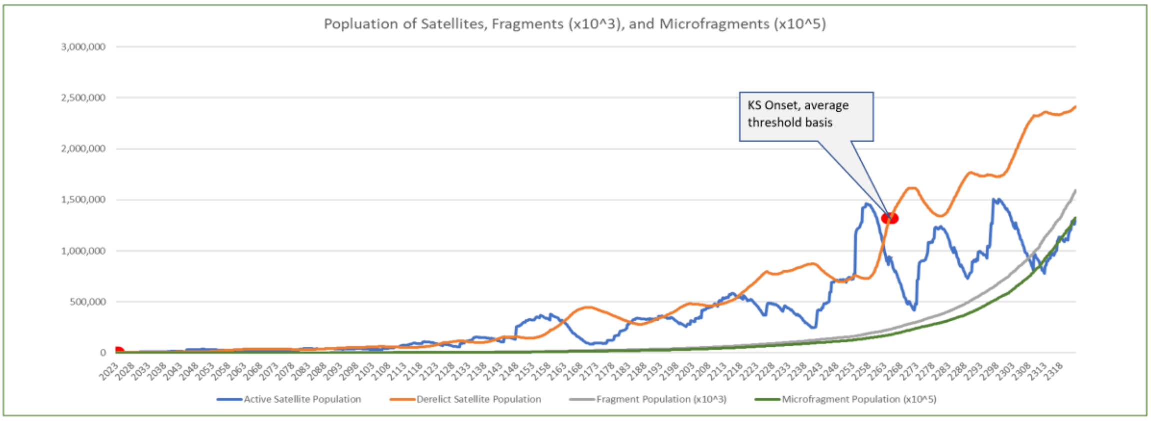

Fig. B.1. Results of model for one of 5,000 runs for base case scenario, showing evolution of the populations for all of the object types in the LEO. This run shows a collapse in year 2265 (average of KS thresholds).

B.2. *Lifespan Threshold for Kessler Syndrome Onset*

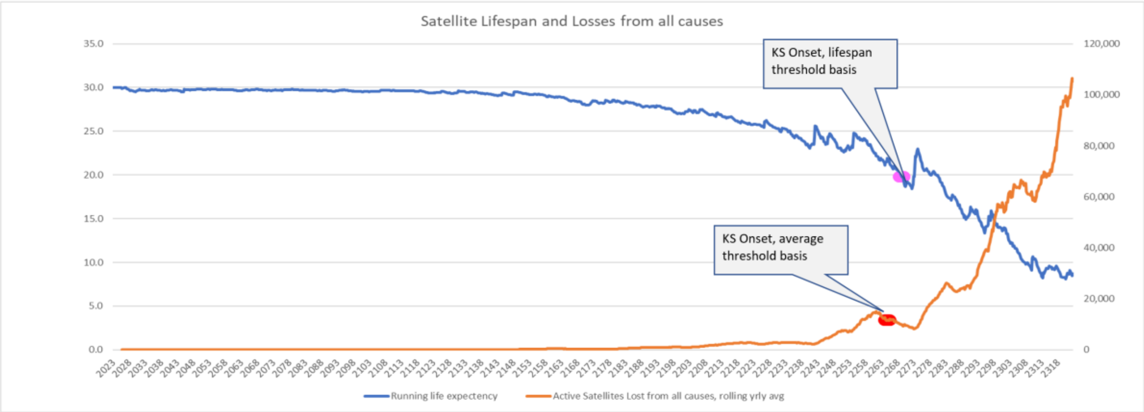

Fig. B.2. Results of model for one of 5,000 runs for base case scenario, showing evolution of satellite average life expectancy and satellites lost from collissions. This run shows a collapse in year 2270 (lifespan threshold).

B.3. *Replacement Threshold for Kessler Syndrome Onset*

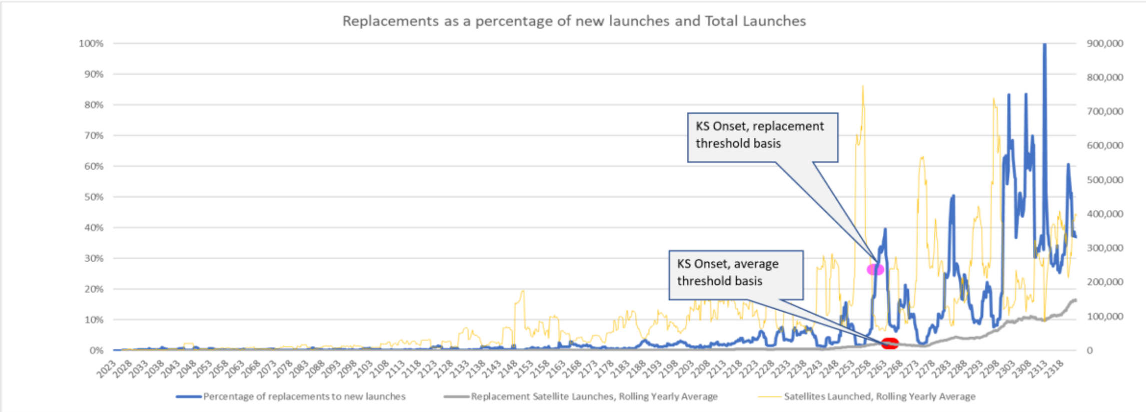

Fig. B.3. Results of model for one of 5,000 runs for base case scenario, showing replacement satellites launched compared to new launches. This run shows a collapse in year 2260 (replacement threshold).

B.4. *Collision Probability Threshold for Kessler Syndrome Onset*

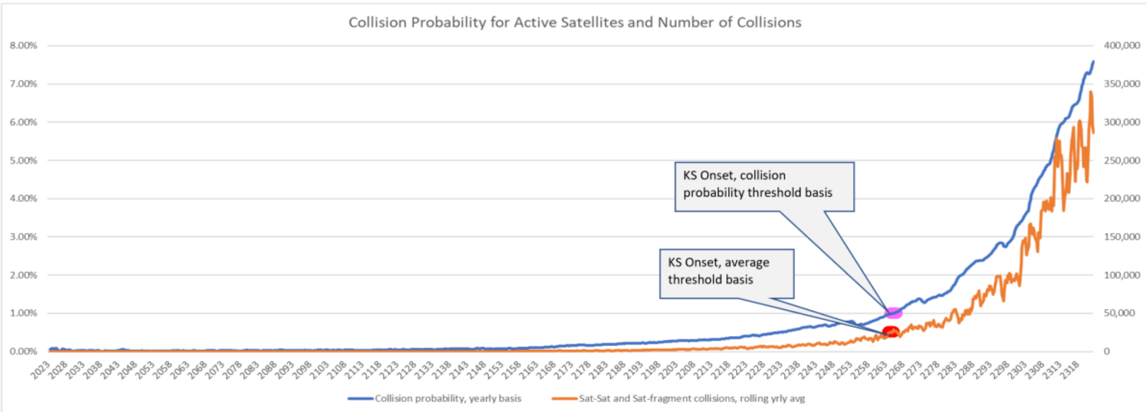

Fig. B.4. Results of model for one of 5,000 runs for base case scenario, collision probability for active satellites and number of satellite-satellite and satellite-fragment collisions. This run shows a collapse in year 2266 (collision probability threshold).

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