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

Julia Hudson
julia.hudson@outlook.com

Modeling the Future Challenge 2023

1. Executive Summary

The global space industry was valued at over $400 billion in 2022, and is expected by Forbes to grow to over $1 trillion by 2040. Most of the assets in space are located in the low Earth orbit (LEO), defined as the region from 400-2,000 km in altitude, and provide essential services for communications, navigation, meteorology, military intelligence, science, and imaging. However, mankind's productive use of the LEO is at risk from increasing counts of debris objects and derelict satellites, which pose collision dangers to active spacecraft. This paper will focus on analyzing the frequency and severity of the risks for spacecraft operations, now and far into the future, and make recommendations for managing those risks.

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. The onset of the KS in the LEO would cause a collapse of the entire space infrastructure and the loss of trillions of value. It is an imperative to all of humanity that this tipping point is never reached.

In order to better understand risks of space operations and the likelihood of the KS chain reaction, the KESSYM model has been developed as a stochastic simulation of the millions of objects in the LEO. The model has been populated with data describing the current year conditions of the LEO drawn from European Space Agency reports, and also with parameters for how the environment will evolve in the future, derived largely from NASA engineering simulations. 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 in order to determine their impacts to space operations.

Numerous strategies are being contemplated that would help to decrease the frequency and severity of catastrophic collisions, which will be categorized in this paper as: hardening of spacecraft against debris, fragmentation prevention, collision avoidance, population management, active debris removal, and a launch moratorium. Each of these mitigations has a cost associated with it, and the KESSYM model provides and economic model as well to score the cost effectiveness of each. The economic model uses published data from NASA and SpaceX on the business of space, along with simple cash flow models to produce its conclusions.

The conclusion drawn from the KESSYM simulation is that the LEO will be unusable within 250 years of today's date; that is, the KS is almost an inevitability in this timeframe in the business-as-usual scenario. Fortunately, the KS can be delayed or avoided altogether if action is taken. The most effective strategy is population management, followed by collision avoidance. All of the other strategies except a launch moratorium also have a positive return on investment. And importantly, the mitigation measures are even more effective when done in combination--implemented together, the KESSYM model predicts that the KS can be deferred indefinitely.

The business of space cannot grow to its potential if the environment of the LEO becomes polluted with debris and derelict satellites. Sustainability is just as important in space as it is on Earth. The KESSYM model developed for this paper uses risk characterization to instruct us how to manage the orbital resources effectively, so that our generation and our descendants can enjoy the promise of this new frontier: a bounty of science, commerce, and exploration as limitless as space itself.

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2. Introduction and Background

Modern life as we know it depends on the space industry. Almost everything we rely on day-to-day is connected to space-based services in some way: wireless internet connections, credit card transactions, GPS navigation, weather reports, entertainment, air travel, agriculture, science, and defense. The space industry is massive and growing fast, with the Space Foundation estimating total worldwide revenues growing from $200 billion in 2009 to over $450 billion in 2022, and projected to top $1 trillion by 2035.

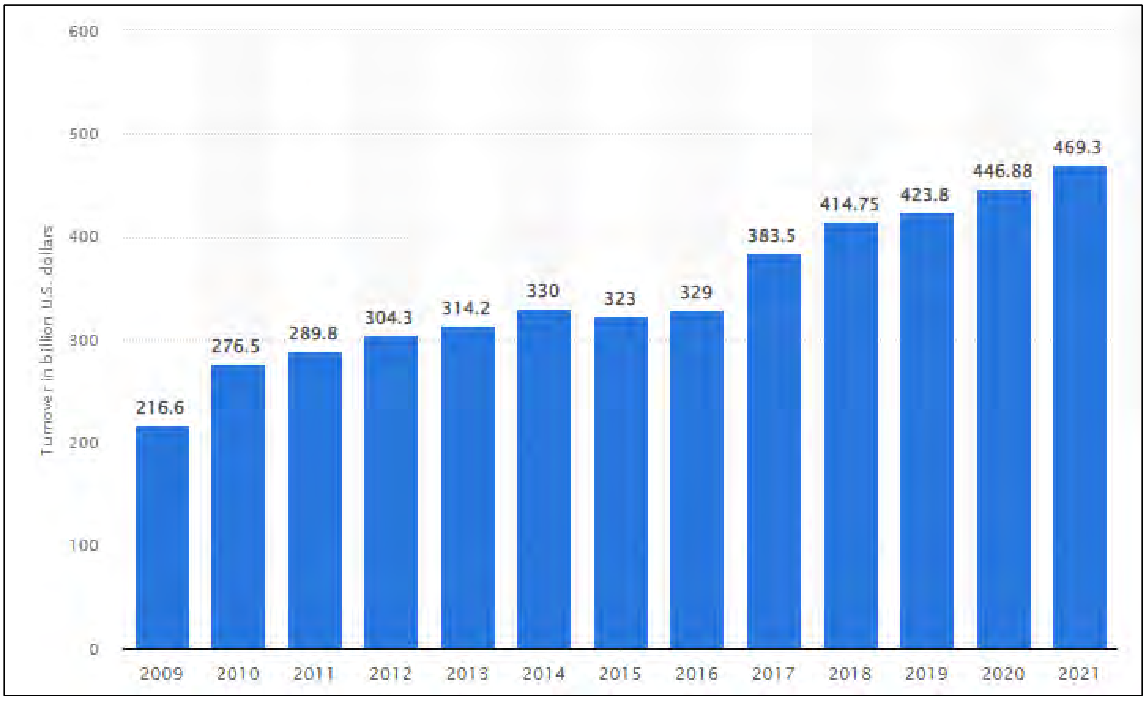


Figure 2-1 Growth in the Space Industry Worldwide 2009-2021 [Space Foundation (2022)]

Whereas the space industry was once led entirely by government agencies such as NASA and the European Space Agency (ESA), private companies are now taking an increasing role, with familiar names such as SpaceX and Blue Origin launch rockets at record rates.

The low Earth orbit (LEO) environment is of particular interest to industry, since it represents the orbital region closest to Earth, easiest to reach and where services such as communications and imaging can be provided most effectively. The consulting firm Deloitte sees the economy of the LEO (as a subset of the entire space industry) growing on its own from $50 billion today to over $300 billion by 2035, in sectors shown here:

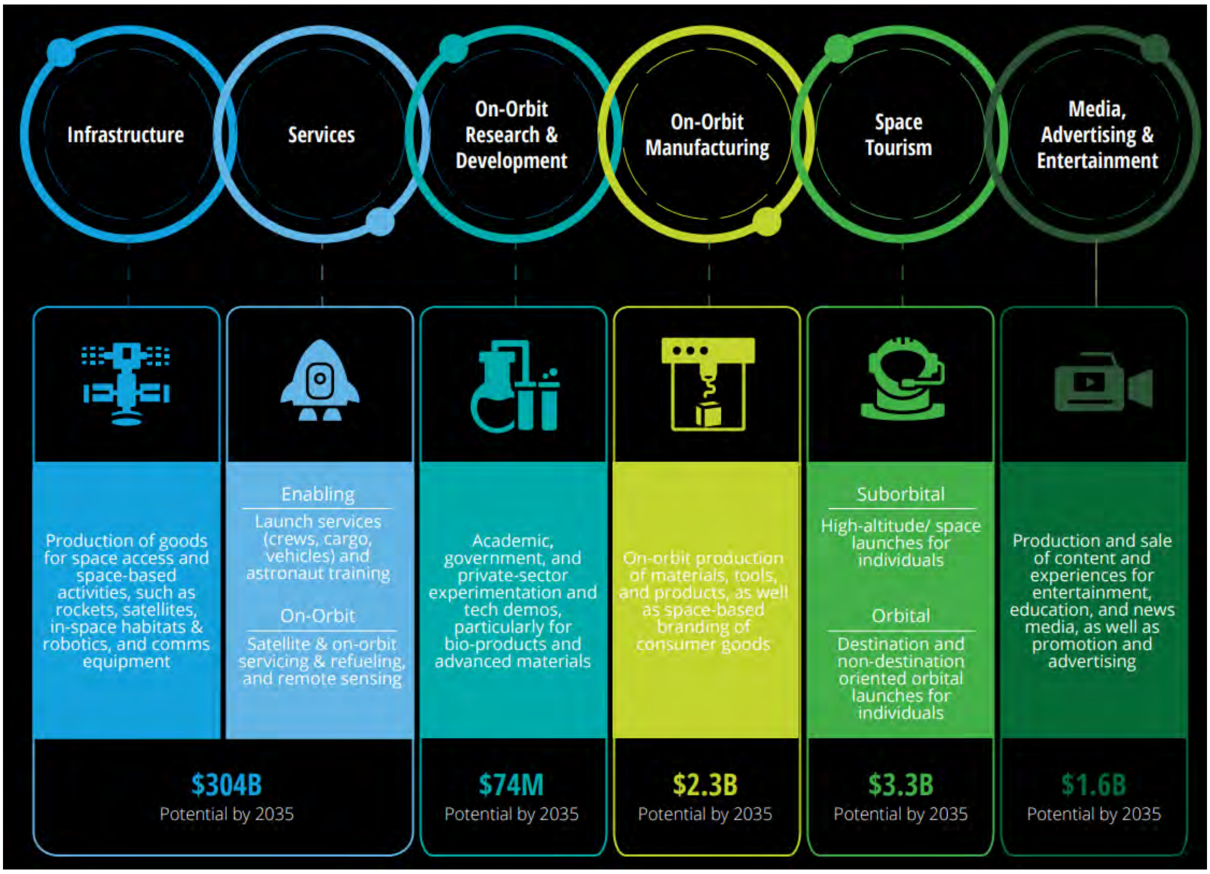


Figure 2-2 Low Earth Orbit Value Chain and Its Economic Potential by 2035 [Deloitte (2022)]

This phenomenal growth in the LEO presents both opportunity and danger. Considering the tremendous investment that will be required to reach these levels of growth, and the significant risks involved in space operations, these operators will be relying on the insurance industry to provide solutions to manage these risks. While the insurance industry collected large premiums from the space business, estimated as $500 million in 2021, there is concern that risks are not well-understood. An industry reporter writes, "76% of respondents to the WEF's Global Risks Perceptions Survey said that international risk mitigation efforts in space were either totally absent or in the earliest stages." [Zisk (2022)] The subset of space operations risk related to orbital debris is the least well-understood.

The focus of this report will be to characterize the frequency and severity of risks posed by the growth in "space junk," that is, the population of derelict spacecraft and debris that remain in orbit from space operations. Every phase of a satellite mission can contribute to debris: there are often fragments released or even entire rocket stages left in orbit after launches; satellites can shed fragments or even spontaneously explode in orbit; satellites that end their mission and not de-orbited can remain as derelicts; and collisions between objects can create clouds of fragments. Objects in the LEO tend to be long-lasting—remaining in orbit from for decades at the lower altitude, or hundreds of years at the higher altitudes—before eventually returning to Earth when their orbit decays.

Since the dawn of the Space Age, the LEO has evolved from an empty frontier to a bustling thoroughfare of commerce. It 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 $8x10^{10}$ 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, we have developed KESSYM (**KES**sler **SY**ndrome **M**odel), which is a stochastic risk simulation of debris and spacecraft in the low Earth orbit. Using KESSYM, we 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? Acts of terrorism or sabotage in the LEO? Or 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: Spacecraft Hardening, Fragmentation Prevention, Collision Avoidance, Population Management, Active Debris Removal, and a Launch moratorium. 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. The mitigation strategies will be considered both on an absolute basis of their effectiveness at reducing the frequency and severity of casualty events, and also on a cost-benefit basis according to relative economics.

3. Data Methodology

3.1. *General Methodology*

The data methodology for the KESSYM model relied on identifying and collecting data and parameters in order to accomplish the key goal: a simulation of millions of objects in the LEO environment and the evolution of that environment over time. KESSYM is fundamentally comprised of three model modules, the Population Model, the Collision Model, and the Economic Model. These will be described in more detail in *Section 4.*

We collected data in four main categories, showing here the category of data and which module it feeds:

Table 1. Data Categories.

Data Type	Types of Data	KESSYM Model Input
Current state of the space environment; General modeling parameters	Population survey of objects; historical reports of launches; Data from object monitoring	Population Model
Growth of the Space Industry	Forecasts of space activity; company business plans	Population Model
Factors Affecting Object Populations	Studies of orbital decay rates; historical debris records	Population Model
Frequency and Impacts of Collisions	Engineering models; historical collision records	Collision Model Population Model
Economic Parameters	Economic studies; business magazines	Economic Model

In terms of types of data, it is important to make the distinction between data collected which is used as a parameter for the model, and data which is used as an absolute input. As an example of a parameter, we used data from NASA on the estimated number of fragments that might be created from the collision of two satellites. This data will be used as the input for a distribution in the Monte Carlo simulation describing the output of a collision event. Alternately, for absolute inputs, we collected data to be used as starting points for the simulation. For example, an estimate from the European Space Agency is used to define the number of microfragments currently in the LEO. This figure is the initial value, and the simulation will predict how this number rises or falls over time. In cases where no data is available, we used our own estimates based on subject matter knowledge. We will note in the section below where estimates were used. It is the goal for future work to continue refining the data methodology and replacing estimates with scientific and engineering results in order to improve the accuracy of the KESSYM model.

Another point to note is that because KESSYM is stochastic simulation, where it makes sense, we will use a distribution to determine the simulation input for a given period, with the type of distribution chosen to reflect historical variability in the parameter or future uncertainty. For example, if in a future year the model is predicting an average of 200 rocket launches worldwide, the model will randomly pick a value from a normal distribution centered around 200 launches in each period. This is a useful technique in Monte Carlo simulation for modeling natural variability, and allows the model to predict not only the most likely outcome, such as the year of the expected KS onset, but also provide the band of 5^{th} percentile / 95^{th} percentile outcomes in order to refine the risk analysis.

We have made every effort to find the most reliable source of data for these starting conditions and parameters, but it must be understood that there are significant uncertainties. For example, as will be seen in *Section 4.2*, the Population Model, the definition of a microfragment is an object in space too small to be detected. Therefore, it is impossible to have a precise count of these objects, and we will rely on estimates from literature. And on top of that, the KESSYM model is intended to be run as a projection hundreds of years into the future, where uncertainties will compound over time. However, despite these limitations in data reliability, the goal of the model can still be achieved, understanding that we are seeking to understand big-picture risk and not exact outcomes.

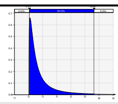
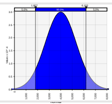
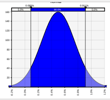
The following sections will describe the sources used for each of these data categories. Each table summarizes most of the input parameters used for the KESSYM model and notes the source basis for the parameter, as well as a thumbnail version of the distribution (if any) used to model inputs with a stochastic component.

3.2. *Current State of the Space Environment; General Modeling 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.*].

Table 2. Current State of the Space Environment - Simulation Inputs.

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	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)]

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
Satellites per rocket	*count*	2 (*f* 1 / 19)		Estimate based on historical and current constellation trends
Average payload mass per rocket initial	*kg*	4,000 (*normal* 1,807 / 6,193)		[ESA (2022)]
Payload mass per rocket, yearly increase	*%/year*	0.50% (*normal* 0.1% / 0.9%)		Estimate based on current trends
Starting fragment population	*count*	1,000,000		[ESA (2022)]
Starting microfragment population	*count*	130,000,000		[ESA (2022)]

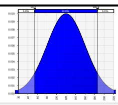
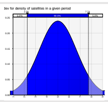
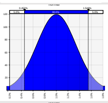
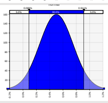
KESSYM also maintains parameters to model the future use of space. There is no way to determine with any certainty what the rate of rocket launches will be 100 years from now, how many satellites will be deployed in the LEO, and how effective future measures to reduce collision risk will be. We have tried to provide a base case set of assumptions that extrapolate current growth in space exploitation to future periods, informed by literature on this topic. The general assumptions for the 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, we 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 average payload of a rocket launched is modeled as a normal distribution with an average of 4,000 kg in the initial year, with 90% of the outcomes being between 1,807 and 6,193 kg. The intent is to model natural variability while also extrapolating future trends.

3.3. *Growth of the Space Industry*

The space industry is poised for massive growth in the decades to come, with new nations joining the rocket club yearly, and corporations such as SpaceX, Virgin Galactic, and Blue Origin accelerating their ambitions. In the KESSYM model, by projecting historical trends into the future, we estimate that the number of rocket launches, the average payload per rocket launch, and the number of satellites in each payload will increase (as satellites get smaller with advances in technology).

Table 3. Growth of the Space Industry - Simulation Inputs.

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
Rocket launches per year	*Count*	120 (*normal* 54 / 186)		Starting point from [ESA (2022)]
Linear increase in launches per year	*Count*	5 (*normal 2.3 / 7.8)*		Estimate of future trends [Diserens (2022)]
Increase in satellites per rocket per year	*Percentage*	1.0% (0.5% / 1.5%)		Estimate based on current constellation trends
Payload mass per rocket, yearly increase	*%/year*	0.50% (*normal* 0.1% / 0.9%)		Estimate based on current trends

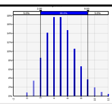
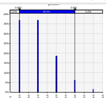
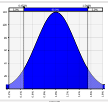
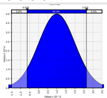
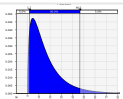
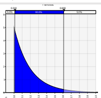
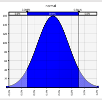
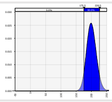
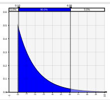
INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
Replacement launches for satellites lost	*Percentage*	50%		Estimate based on expected need to replace satellite functions
Time delay for replacement launches	*Months*	24		Estimate of time to prepare and launch new mission

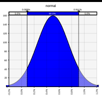
Note also the concept of replacement launches in the model. It is assumed that when satellites are destroyed before the end of their mission, some number of replacement satellites will be launched to replace their functions. This is a reasonable basis on the assumption that operators would insure their spacecraft against destruction. See *Section 5.2* for more discussion of insurance premiums.

3.4. *Factors Affecting Object Populations*

The following parameters which affect the evolution of the population of the satellite, fragment, and microfragment populations are provided here. Some of the data provides for rates of increase, such as fragments generated during rocket launches, and some of the data shows the rates of attrition from the population. 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 data behind these parameters comes from the literature cited here:

Table 4. Factors Affecting Object Populations - Simulation Inputs.

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
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
Likelihood of a disabled satellite remaining controlled	*%*	25%		Estimate
Loss of control of derelict satellites	*%/year*	1.00% (*normal* 0.5% / 1.5%)		Estimate of yearly attrition
Risk of explosion per satellite	*percentage*	0.001% (*normal* 0% / 0.003%)		Estimate from historical [Anz-Meador et al. (2018)]
Fragments per launch	*Count/launch*	10 (*Pearson* 2 / 46)		[Diserens (2022)]
Fragments from operations	*count/ satellite/year*	0.1 (*Pareto2* 0.01 / 0.6)		[Diserens (2022)]
Fragment decay rate	*%/year*	0.50% (*normal* 0.1% / 0.9%)		Estimate from decay model, natural decay of 200 years [Lewis (2020b)]
Microfragments per launch	*count/satellite*	200 (*Pearson* 176 / 226)		[Diserens (2022)]
Microfragments from operations	*count/ satellite/year*	1 (*Pareto2* 0 / 6)		[Diserens (2022)]

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
Microfragment decay rate	*%/year*	0.5% (*normal* 0.1% / 0.9%)		Estimate from decay model [Lewis (2020b)], natural decay of 200 years

The rates of decay are very important to the operation of the model and represent the primary means by which objects are removed from the LEO. Increasingly at the lower bounds of the LEO, air particles from the Earth's atmosphere exert drag on the objects, which causes them to gradually decelerate, lowering their orbits, until they fall into the atmosphere. Once entering the atmosphere, most objects except very large ones will burn up prior to hitting the earth. Using the estimates from literature regarding the average lifespan of objects in the LEO, the reciprocal relationship is used:

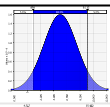
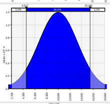
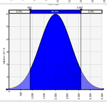
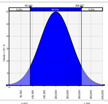
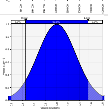
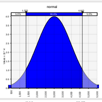
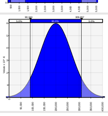
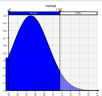
$$T = 1/\lambda \tag{1}$$

Where T is the lifespan of the object and λ is the rate of decay. Therefore, a derelict satellite normally de-orbited within 20 years would have a 1/20 = 5% yearly rate of decay.

3.5. *Frequency and Impact of Collisions*

There is much data in the literature from engineering simulations regarding the frequency of collisions between objects in orbit, and also the severity of the impacts that occur after collisions. These data are aggregated here as parameters for the Collision Model within KESSYM.

Table 5. Frequency and Impact of Collisions - Simulation Inputs.

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
Fragments per explosion	*count*	5,000 (*normal* 888 / 9,112)		Estimate from collision model [Kessler (1978)]
Fragments per sat-sat collision	*count*	10,000 (*normal* 4,517 / 15,483)		Estimate from collision model [Kessler (1978)]
Fragments from fragment-sat destruction	*count*	2,000 (*normal* 903 / 3,097)		Estimate from collision model [Kessler (1978)]
Fragments from microfragment-sat collisions	*count*	0.0100 (*normal*)		Estimate from collision model[Kessler (1978)]
Microfragments per explosion	*count*	200,000 (*normal* 90,000 / 310,000)		Estimate from collision model [Kessler (1978)]
Microfragments per sat-sat collision	*count*	1,000,000 (*normal* 450,000 / 1,500,000)		Estimate from collision model [Kessler (1978)]
Microfragments from fragment-sat collision	*count*	3,000 (*normal* 1,350 / 4,650)		Estimate from collision model [Kessler (1978)]
Microfragments from fragment-sat destruction	*count*	200,000 (*normal* 90,000 / 310,000)		Estimate from collision model [Kessler (1978)]
Microfragments from microfragment-sat collisions	*count*	0.50 (normal 0 / 1)		Estimate from collision model [Kessler (1978)]

INPUTS	Units	Simulation Value (*distribution* P5 / P95)	Distribution thumbnail	Notes / Source
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)]
Likelihood of avoiding active satellite collision	*%*	50%		Estimate based 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

As can be seen, certain of these parameters such as collision cross-sections and likelihood of avoiding collision affect the frequency of catastrophic events. Other parameters such as the number of fragments generated from a collision, or the likelihood of a disabling strike affect the severity of these events.

3.6. *Economic Parameters*

In order to understand the severity of casualty events from an economic perspective, and also to be able to rank recommendations on a cost-benefit basis, we have developed an Economic Model which is integrated into KESSYM. For purposes of this model, each individual satellite is assumed to be a “business.” That is, money is invested to construct and launch the satellite, and then it returns income during its useful life by providing services. Even though many satellites are non-commercial, such as research or military satellites, it will be assumed that they have equivalent non-economic returns, such as the value of scientific data or military intelligence collected. The input parameters for the economic model were derived from literature [NASA (2010)] and are summarized here:

Table 6. Economic Parameters - Simulation Inputs.

Input Category	Value	Mitigation Category	Cost
Cost to construct ($/kg)	$100,000	Cost of hardening ($/kg)	$2,000
Cost to launch ($/kg)	$20,000	Cost of fragmentation prevention ($/kg)	$2,000
Investor multiple of invested capital (MOIC)	4.0x[a]	Cost of collision avoidance	$2,000/kg + $50,000 per satellite
Time frame for analysis	250 years	Cost of population management	$2,000 per kg + $100M per year

[a] Return of the invested capital + 3x more; equivalent to a 25% internal rate of return (IRR).

This paper will also use this economic data to consider how insurance costs might increase due to growing hazards in orbit. The cost to insure satellite launches and operations will be an important factor in the business of space. Note that for simplicity of modeling inflation is not used in the economic model; it is assumed that increases in cost over time are offset by improvements in the cost-effectiveness of technology. The mitigation measures listed in the right-hand column will be detailed in *Section 6.1.*

4. Mathematics Methodology

The KESSYM model was developed to be a comprehensive rapid stochastic simulation model of the entire LEO environment and is comprised of three main modules. 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 Model to simulate collision risks and outcomes. Finally, the model includes an Economic Model, which provides the engine for cost-benefit analysis.

KESSYM is not intended to replace current models for space debris, but rather is a "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 estimate the frequency and severity of casualty events in the LEO in the future. Importantly, we can also characterize the likelihood of the KS tipping point, the most severe casualty scenario, 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.

4.1. *Stochastic Risk Engine*

As is typical in Monte Carlo simulations, the KESSYM model employs the notion of a "state," that is the condition of all the objects in the LEO at a given moment. The state is characterized by populations of the different object types, their average age and mass, and some global parameters such as the date. The model then moves ahead a single increment of time and records all the events and changes in state. The parameters for the scenario determine some of the changes in state, such as how many rockets are launched or how many satellites are decommissioned. There are many random inputs to this change in state, such as probabilistic outcomes of whether or not collisions happen. The model also has a scenario manager, which then determines if random events such as solar flares occur, and the impact of any mitigations being employed. Once all the changes to the state are recorded, that becomes the new state, and so on for hundreds of years into the future.

The KESSYM model is flexible in terms of time increments between each change of state, 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. Choosing the time increment is an exercise in balance between model usability and accuracy.

In terms of software used, 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.

For the stochastic inputs, 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 discrete 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 risk 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.

4.2. *Population Model*

The KESSYM model maintains a running population model of three categories of objects in the LEO: microfragments, fragments, and satellites. This is intended to be the minimum number of categories 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 7. 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	8,000

[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. The flow of the population model is summarized in *Table 3*.

Table 8. Events Affecting Population Model[a].

	Active Satellites	Derelict Satellites	Fragments	Microfragments
Starting Population	2,000	6,000	1,000,000	130,000,000
Satellites Launched	Increased by (rockets launched) x (satellites per rocket)		+10 per rocket	+1000 per rocket
Replacement satellites launched	+50% of satellites lost 2 years prior		+10 per rocket	+1000 per rocket
Accidental explosions	-0.001% for each satellite	-0.001% for each satellite	+5,000 per explosion	+200,000 per explosion
War and Terrorism	-500 for war, -10 for terrorism		+5,000 per each destroyed	+200,000 per each destroyed
Solar Flare Event	4% of active satellites become derelict			
Collisions	See Collision Model			
Intentional decommission	(-) end of life satellites	(+) end of life satellites		
Decay in orbit and re-enter atmosphere		-5% of controlled -1% uncontrolled	-0.5% decay (200-year life)	0.5% decay (200-year life)
Active Removal			-10,000 per year	
Legend	*Increase in Population*		*Decrease in Population*	

[a]*Note that impacts to population are shown as the average impact; distributions are used in actual model*

Table 8 shows that there are many circumstances that increase debris population but limited means to reduce it, namely natural orbital decay and active removal. Another way to think about the KS onset is in terms of the relative rates of accumulation of debris and disposal in the LEO. If the accumulation is faster, then the debris population will build and eventually reach the tipping point to trigger the KS.

4.3. *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.

Following the example of some space debris models other models [Bradley (2009)], we used collision probability calculations borrowed from chemistry--the ideal gas model. The assumption is that the objects in the LEO will have similar characteristics to particles in a gas (though without the concept of container walls). 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:

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

The ideal gas-based approach will provide a good compromise between accuracy and usability, and not require empirical tracking of each individual object, which would be computationally prohibitive. 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:

$$\boldsymbol{Z_{ab} = C_0 \times A_s \times D_a \times D_b} \tag{3}$$

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. These parameters are defined numerically in *Section 3.5.*

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.

The interactions of the different objects are summarized in the matrix below in *Table 4*.

* Currently approximately 50,000 debris objects are actively tracked, out of an estimated population of 1,000,000 fragment-size objects. Therefore, it is estimated that 50,000/1,000,0000=5% of fragment-satellite collisions could be avoided. It is assumed that all satellites are tracked, and therefore two active satellites have a 50% + 50% likelihood of avoiding collision.

Table 9. Collision Model Matrix.

	Active Satellites	Derelict Satellites	Fragments	Microfragments
Active Satellites	• Collision likelihood increases with population • Can be avoided (50% each satellite) • Certain destruction • 10,000 fragments • 1,000,000 microfragments			
Derelict Satellites	• Collision likelihood increases with population • Can be avoided (50%) • Certain destruction • 10,000 fragments • 1,000,000 microfragments	• Collision likelihood increases with population • Certain destruction • 10,000 fragments • 1,000,000 microfragments		
Fragments	• Collision likelihood increases with population • May destroy (6%) or disable (60%) satellite • Destruction creates 2,000 fragments, or 6,000 with explosion (10% of destroyed) and 200,000 microfragments • Can be avoided (5%)	• Collision likelihood increases with population • May destroy (6%) satellite • Destruction creates 2,000 fragments, or 6,000 with explosion (10% of destroyed) and 200,000 microfragments	• Collisions not modeled	
Microfragments	• Collision likelihood increases with population • May destroy (0.1%) or disable (1%) satellite, explosion for 10% of destroyed • Creates 0.01 fragments and 0.5 microfragments (or 6,000/200,000 with explosion) • Cannot be avoided, but satellites can be hardened	• Collision likelihood increases with population • May destroy (0.1%) satellites, explosion for 10% of destroyed • Creates 0.01 fragments and 0.5 (or 6,000/200,000 with explosion) • Cannot be avoided, but satellites can be hardened	• Collisions not modeled	• Collisions not modeled

4.4. *Economic Model*

An economic model was employed in order to provide a basis for comparison of the risk mitigation techniques (see *Section 6*). The base economic case assumed no mitigation measures in place, and then 5,000 runs were done with each of the mitigations in place individually. The total cost of the mitigation program could then be compared to the total value saved by the mitigation to provide a benefit:cost ratio.

In order to be able to forecast the economic severity of a casualty event, each satellite is considered as a "business" using the input parameters shown in *Section 3.6.* Based on these inputs, we created a cash flow model for each satellite, here using a 1,000 kg satellite as an example:

Figure 4-1. Satellite Cash Flow Model.

Assuming that the satellite survives for its entire useful life of 15 years, the model shows that the net profit will eventually be $360M (an investment of $120M, with eventually $480M returned). Using the conventional investment metric of internal rate of return (IRR), this calculates to a 26% IRR (pre-tax), which would be sufficient to attract investment [*NASA* (2010a)].

This model calculates the loss of value if the satellite destroyed before its intended end of life. In the example shown, the satellite is destroyed by a collision at the end of year 8. Therefore, the expected revenue from years 9-15 is lost, visualized as the area of the red triangle. That area is the aggregate economic cost of the collision event. The economic model can be summarized as:

$$(\boldsymbol{Revenue\ per\ year}) = (\boldsymbol{total\ cost\ per\ kg}) \times (\boldsymbol{mass\ of\ satellite}) \times (\boldsymbol{4.0x\ MOIC}) \div (\boldsymbol{lifespan}) \quad (4)$$

$$(\boldsymbol{Loss\ of\ value}) = [\boldsymbol{lifespan} - (\boldsymbol{year\ of\ destruction})] \times (\boldsymbol{Revenue\ per\ year}) \quad (5)$$

The KESSYM model was run using this methodology for value lost from destruction of satellites, and also including the cost for the mitigation programs listed. As seen in *Table 6*, the programs in general are modeled to cost individually about 2% of the cost of the original satellite, with repeated investments over time producing improved benefits as the technology matures [NASA (2010b)]. The Launch Moratorium is a special case in that it does not have a particular cash investment cost to implement. Instead, the cost of this mitigant is assumed to be the lifetime income of satellites launched during the year that the moratorium is in place--that is, the total of profits deferred by the moratorium.

For each mitigant, benefit:cost ratio was then calculated, in order to determine the most efficient strategy for maintaining the safety of the LEO environment.

5. Risk Analysis

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.

5.1. *The Kessler Syndrome (KS)*

The key outputs sought from the KESSYM model are the frequency of severity of risks to space operations, with the potential onset of the KS as the most severe outcome of all. Therefore, 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 15 years, and if due to collisions the average lifespan goes below 10 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.

5.2. *Risk Analysis Results*

Given that the KS is essentially the event in space operations when the frequency and severity of casualty events both increase exponentially, the first goal of the KESSYM modeling will be to characterize the risk of the KS onset:

(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 business-as-usual scenario:

Table 10. 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 2 provides a histogram of the simulation results for the AVERAGE row:

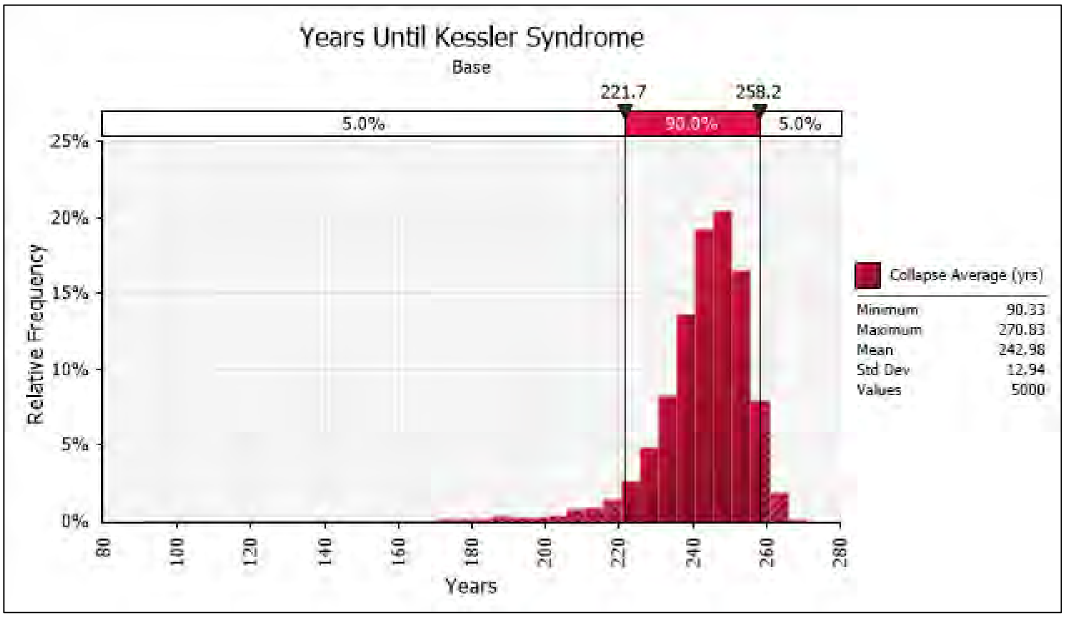


Figure 5-1. Results of 5,000 300-year simulations, plotting relative frequency of collapse year based on the average of the three KS definitions. Note P5/P95 values of 222/258 years, as well as simulation low/high of 90/271.

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.

5.3. *Kessler Syndrome Risk Trends*

As stakeholders in space think about the risk of the KS occurring the future, a question arises: will we have any warning? Will the cascade of debris occur in a single week, or month, year, decade, or century?

(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 11. 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 a rapid runaway chain reaction when it occurs, happening suddenly on the order of days or months. It is a tipping point that occurs in slow motion; the model predicts that humanity will have a few decades of warning in which to take corrective action, estimated at 18-44 years. One question that could be explored in future modeling is if corrective action is even possible. That is, once these warning points reached, it is too late to implement the mitigation measures or is the system collapse unavoidable?

Another way that we could think about the kind of warning signs of a KS onset would be to consider what would be the cost of insuring satellites. The insurance industry would likely price the policy for a satellite according to the likelihood of a casualty event, that is, the loss of the satellite. For this analysis, the KESSYM model was used to make calculation from the insurance company's point of view, looking at a given time period and estimating the risk of a casualty at some point in the satellite's useful lifespan. This total risk of loss is the compounded probability of it being destroyed each time period for the remainder of its lifespan:

$$\boldsymbol{R_{total} = 1 - \prod_{n}^{n+lifespan}(1 - R_{year\ n})} \tag{6}$$

Where R_{total} is the risk of a loss over the satellite's whole lifespan, $R_{year\ n}$ is the risk of a loss in a given year n. Using this method, we looked at the expected years into the future when R_{total} would reach certain thresholds of 5%, 10%, and 15%. We used these to represent milestones where the premiums required to insure satellites might become so expensive that they curtailed the industry's ability to function.

Table 12. Expected year that lifetime risk of loss exceeds thresholds.

Threshold	Years of warning provided	P5 / P95
5% risk of loss during lifetime	54	34 / 70
10% risk of loss during lifetime	21	12 / 31
15% risk of loss during lifetime	3	(6) / 7

Note that the warning times here for the 5% threshold, expected to be 54 years on average, is higher than the average of 31 years from the analysis from the KS thresholds. The takeaway from this analysis is that the insurance industry may end up providing the most reliable early signal to the space industry and agencies that the KS onset is imminent.

5.4. *Kessler Syndrome Additional Hazards*

"Always expect the unexpected" goes the proverb. Applying that mindset to the KESSYM model, we have analyzed the impact of unknown, unpredictable events on the KS onset.

(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 13. 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.

This analysis on discrete hazard events might be of use to the insurance industry. It signals that the impacts of war, terrorism or natural disasters are generally constrained to the systems impacted, but do not spill over in a major way to the orbital environment as a whole. In general, the greatest risk to the LEO is simply overcrowding. This is the primary risk that insurers in space will need to plan for.

6. Recommendations

6.1. *Mitigation Measures*

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:

- **Spacecraft Hardening:** Implementation of design changes, materials, and redundancy to make spacecraft less susceptible to damage from small particles and debris in orbit
- **Fragmentation Prevention:** Technical standards, design changes, procedures, and regulations to reduce fragments created during launches, accidents, spontaneous explosions, and from deterioration over time
- **Collision Avoidance:** Systems to predict collisions based on detection of threatening objects, and protocols and procedures for craft to navigate out of danger; integration of land-based or space-based monitoring operations with satellite operators; provision of extra fuel on spacecraft to increase lifetime number of maneuvers
- **Population Management:** Policies, procedures, regulations to remove satellites from orbit after their useful life, reducing the population of derelict satellites; requirements that every satellite launch includes a decommissioning plan
- **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, ranging from nets to magnets to harpoons 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 our 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.

The KESSYM model is flexible and extensible, so to the extent that new strategies are developed that do not neatly fit into one of these categories, they could be added to the model logic in later revisions. The next section will analyze how effective each of these measures are in terms of delaying the onset of the KS, which is a useful way to quantify reductions in the likelihood and severity of casualty events. *Section 6.3* will then use the costs assigned to the strategy in the Economic Model to evaluate their relative cost effectiveness.

6.2. *Risk Reduction from Mitigation Measures*

Now that we have analyzed factors affecting the frequency and severity of catastrophic events in space, it’s time to provide concrete recommendations:

(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 14. Impact of mitigation measures to Kessler Syndrome onset.

Mitigation measure	**Degree of mitigation**	**Change to KS Onset**[a]
Spacecraft Hardening	-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 100 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. The Launch Moratorium is effective at reducing KS risk, though it is a costly strategy, as we will see in the next section. 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.

The strongest recommendation to come out of the KESSYM model is that Population Management strategy should be implemented *now*. This strategy doesn't even take a great deal of new technology; it is more a matter of regulatory enforcement of the principle "put your toys away when you are done with them." That is, space agencies and companies can launch satellites, but they must be diligent about removing those satellites from orbit when their mission is completed.

6.3. *Cost-Benefit Analysis of Mitigation Measures*

Using the methodology described earlier in *Section 4.4*, we determined the total cost of the mitigants and also the total value saved by each one individually. We chose a point 250 years in the future as the horizon to calculate these values, as that was generally the time at or near the KS onset point for the scenario, and the time when the benefits would have sufficient time to accrue. The results are summarized here:

Table 15. Cost and Benefits for Mitigation Measures (250 year basis).

Mitigant	Total Cost ($B)	Total Value ($B)	Benefit-to-Cost Ratio
Spacecraft Hardening	(2,152)	4,438	2.1
Fragmentation Prevention	(2,160)	4,481	2.1
Collision Avoidance	(2,333)	9,309	4.0
Population Management	(2,312)	13,116	5.7
Active Removal	(1,393)	2,025	1.5
Launch Moratorium (LM)	(99,656)	11,159	0.1
All Mitigants (except LM)	(7,306)	57,811	7.9

The Population Management strategy is a clear winner, with Collision Avoidance in second. These findings are consistent with the risk reduction analysis from the prior section. The remaining strategies seem to have positive returns on investment and similar cost efficiencies, except for the Launch Moratorium, which is estimated to destroy roughly 10x more value than it creates.

Interestingly, the analysis also shows that combining mitigants is a highly effective strategy. The benefit:cost ratio for the All Mitigants case exceeds any of the individual strategies. This makes sense when considering the results in *Section 6.2*, which forecast that the KS could be delayed indefinitely when all the measures were applied. Because the KS onset is prevented, far less value is lost from collisions--clearly a case when the whole is greater than the sum of its parts.

Another question arises from this analysis: what would be the incremental impact of increasing each mitigation measure individually? As a sensitivity, a batch of simulations was run with each mitigant implemented for twice the impact at twice the cost. The results are here:

Table 16. Cost and Benefits for x2 and Mitigation Cases (250 year basis).

Mitigant	Incremental Cost ($B)	Incremental Value ($B	Incremental 2x Benefit-to-Cost Ratio
Hardening x2	(2,099)	465	0.2
Fragmentation Prevention x2	(2,117)	515	0.2
Collision Avoidance x2	(2,169)	507	0.2
Population Management x2	(1,324)	(13)	(0.0)
Active Removal x2	(3,331)	3,857	1.2
Launch Moratorium (LM) x2	(766)	(23)	(0.0)

The 2x cases all show significantly diminishing returns for the incremental investment in additional capacity, with only the Active Removal strategy showing a ratio of greater than one. An avenue for further research could be to find the optimal amount of investment in each mitigant.

The overall recommendations from the KESSYM model can be summarized as:

- Population Management strategies should be implemented first, followed by Collision Avoidance strategies
- Spacecraft Hardening, Fragmentation Prevention, and Active Debris Removal strategies can all achieve a positive return on investment
- The most effective strategy is to apply all of the mitigants, further increasing return on investment

7. 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% likelihood it could be as soon as 100 years from now.

Destructive events in the LEO such as war, terrorism, or periods of active solar flare activity are expected to have some, but not massive, 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 of 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.

Considered on a cost-benefit basis, the strategy of Population Management is by far the most effective, with a benefit:cost ratio of 7.1. For this strategy to be implemented, the average time to de-orbit derelict satellites needs to move from 20+ years to 5 years or under. This could be done with joint national regulation, backed by some form of enforcement. The next most effective strategy, with a 3.2 benefit:cost ratio is Collision Avoidance, which requires the implementation of monitoring networks for debris, and systems of communication and coordination to make rapid adjustments to avoid impacts.

The other strategies of Spacecraft Hardening, Fragmentation Prevention, and Active Debris Removal are all reasonably effective, with benefit:cost in the 2-2.5 range. The Launch Moratorium is not an effective strategy, scoring only a 0.1 on benefit:cost. Importantly, the strategy of combining all of the mitigation strategies (except moratorium) provides outsize benefits, with a combined benefit:cost of 7.1. The recommendation from the KESSYM model is for an all-of-the-above approach, led by Population Management.

The 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.

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Appendix A. Example Simulation Run

For illustrative purposes, we 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.

A.1. *Population Model*

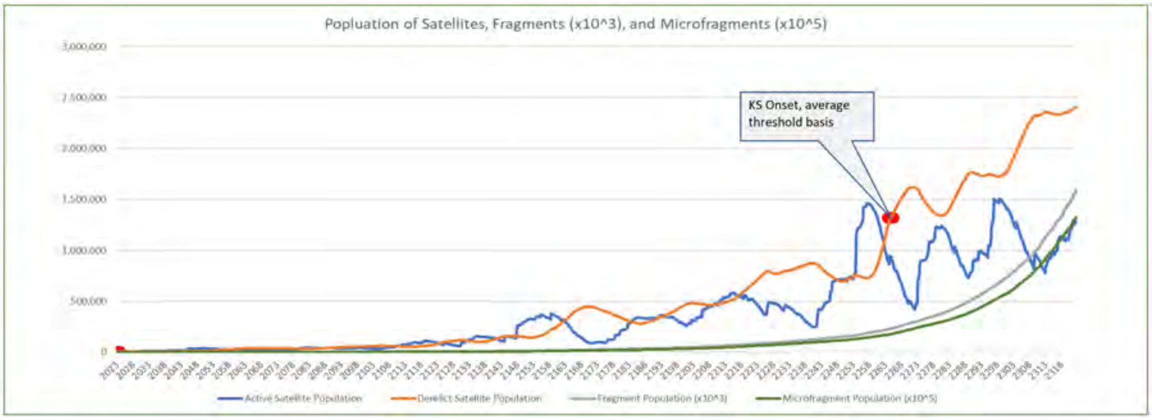

Fig. A.1. Results of model for one of 5,000 runs for base case scenario, showing evolution of the populations for all of the object types in the LEO. This run shows a collapse in year 2265 (average of KS thresholds).

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

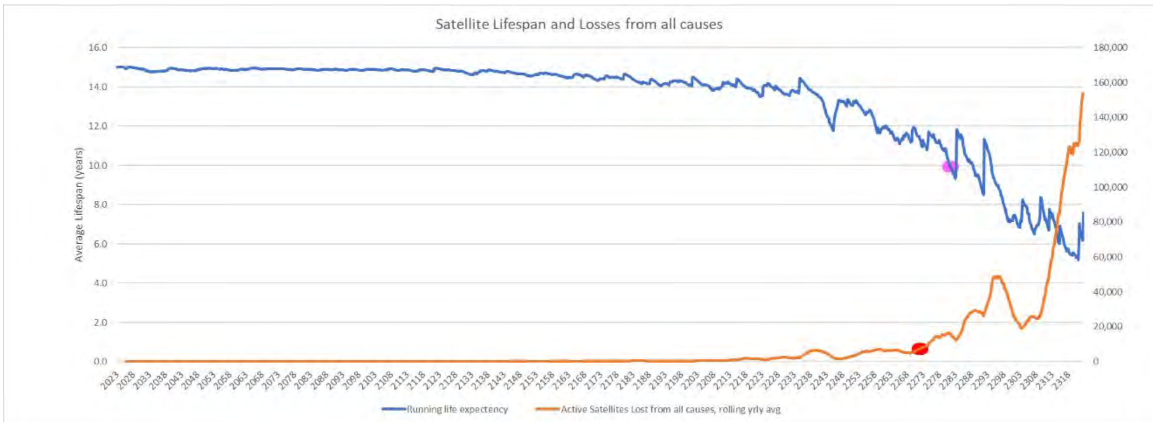

Fig. A.2. Results of model for one of 5,000 runs for base case scenario, showing evolution of satellite average life expectancy and satellites lost from collisions. This run shows a collapse in year 2283 (lifespan threshold).

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

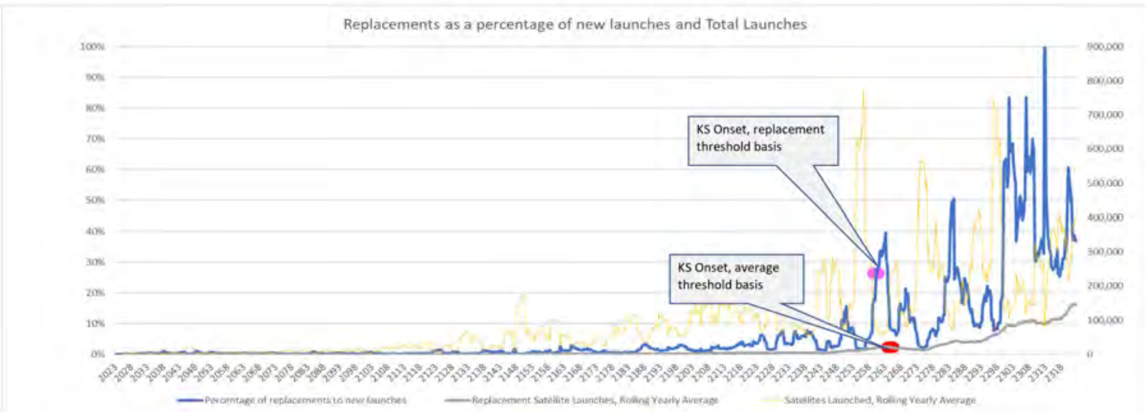

Fig. A.3. Results of model for one of 5,000 runs for base case scenario, showing replacement satellites launched compared to new launches. This run shows a collapse in year 2260 (replacement threshold).

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

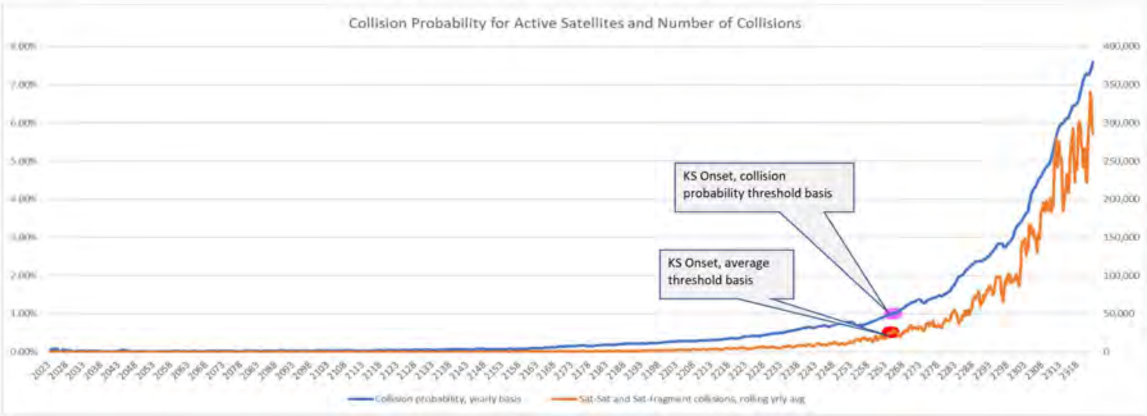

Fig. A.4. Results of model for one of 5,000 runs for base case scenario, collision probability for active satellites and number of satellite-satellite and satellite-fragment collisions. This run shows a collapse in year 2266 (collision probability threshold).

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