**Space Debris Modeling and Simulation**

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ISAT 290, Spring 2022

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**Introduction**

This project set out to help understand the growing space debris problem in low earth Orbit (LEO), we set to model and simulate satellites in orbit, and whether they were damaged, retired, or active. We also hoped to understand the different variables, such as space debris and deorbiting, and if a satellite is active, retired, or damaged and how we can simulate change in the amount of each there are. We first developed a CLD for our system and for our satellites and then moved into systems analysis and simulations where we developed our model of the satellites and then added other variables to interact with. After modeling and running various simulations, it was found that a mandatory deorbit policy has potential to remove satellites from LOE depending on the variables such as compliance rate and the time it takes to deorbit. We also simulated and found how space debris interacts with satellites in LEO.

**Problem Statement**

The growing amount of space debris in low earth orbit (LEO) threatens our ability to use satellites in the future. Satellites are an essential part of our everyday life and provide a lot of information for humans, however with the increasing risk of space debris and the risk of mega-constellations there is a greater possibility for collisions. This space debris problem began in the Cold War and has escalated since then with multiple satellites being launched from private and government space agencies, such as NASA, LeoLabs, and JAXA. This increase in satellites goes hand in hand with the increase in the amount of space debris, such as old rockets or satellites, fragments from other collisions, and other objects in low earth orbit, specifically 750 – 850 km away from Earth. Another increase in satellites is due to mega-constellations by space businesses, and that these mega-constellations greatly increase in the number of satellites in orbit which increase the risk of collisions and space debris.

The increasing collisions and debris in the LEO are risking the lives of the astronauts, the people on Earth, as well as increasing the risk for space businesses such as SpaceX. With SpaceX and other companies launching their own satellites to form mega-constellations it greatly increases the amount of space debris which could lead to major issues in the future with increasing collisions and the disruption of satellites and other space craft. In the future years more will have to be done to counteract these growing problems and more enforcement with laws and regulations regarding space debris will have to be enacted to help resolve the issue.

**Background**

The rocket that bore Sputnik, the first satellite humans ever put into space in 1957, was the first ever piece of space debris. After that the Cold War and more specifically the Space Race took off and the United States and Soviet Union really began the space debris problem and since 1957 it is estimated the US and Soviets have had over 4,000 space launches. Since the end of the Space Race there have been many other private and government space agencies putting satellites into space and contributing to the space debris issue. Many countries each have their own space agencies and work on getting satellites into space, for example the French medium resolution satellite Spot-1, launched in 1986. The Spot-1 satellite was one of the first French satellites and the rocket body that launched Spot-1 had an accidental explosion and launched 492 pieces of debris into LOE in1986. Fengyun-1C, a Chinese weather satellite, was one among hundreds of other satellites that China has launched into space, however Fengyun-1C was deliberately destroyed in 2007 and catalogued 3,218 pieces of debris. In 2009 there was another collision between the United States satellite Iridium 33 and the Russian satellite Cosmos 2251, which produced over 2,000 large trackable pieces of space debris, with hundreds of other smaller pieces that are not trackable. These 4 events have launched over 5,000 pieces of debris into orbit and are only a fraction of the total amount of debris in LEO. There have been many other launches and satellite breakups by other government space agencies, as well as private space agencies that has contributed to the amount of debris in orbit. Along with that the more recent introduction of mega-constellations, such as SpaceX, the amount of satellites and the amount of space debris in LEO is expected to dramatically increase.

With the now millions of pieces of fragmented debris in orbit it is a cause for concern and while space agencies and governments have known about this and have tried to remedy the amount of debris in LOE, it has not been enough and there will need to be more regulation and mitigation methods to effectively remove space debris from orbit. Action has been taken before, such as that with Ronald Reagan and his National Space Policy in 1988. This was the first orbital debris mitigation regulation put into a countries space policy and set an example to other nations to start including new space policy. This led to other leading space agencies updating their own national guidelines, such as Japan in 1996, France in 1999, Russia in 2000, and China in 2005. While all of these did help and during that time frame the amount of space debris in orbit was rather fixed and steady, but it still did not fix the problem and that there were still collisions and there was still a lot of space debris, such as decommissioned satellites in LOE. Another method is tracking orbital debris and then creating collision avoidance technology so that spacecraft and satellites can perform a collision-avoidance maneuver. Another method, besides putting out regulation regarding spacecraft and satellites or collision avoidance technology, is to physically remove the debris from orbit. This could be done with tethers, laser, or space tugs, all of which may only work for smaller or larger debris. Another tactic would be to push debris out further into space or attempt reentry to the atmosphere and back to Earth, which is another issue that must be solved. Each of these come with their own risk as removing debris from the atmosphere but also making sure to bring the debris back safely down to Earth so that it can burn up but also not pose a threat to the people of Earth on reentry. Mitigation is a topic that must be discussed as the world pushes forward with space exploration and satellites, specifically mega-constellations, and their forthcoming effect on the issue of space debris in LEO.

Space debris has so many aspects and there is no 1 solution for this. Government has put policy and tried different mitigation measures to lower the amount of space debris, but it has not all been successful and that none of them have solved the abundance of space debris that is in LEO. There is also no 1 solution because of the systems involved and how much goes into the problem, there are natural blockades stopping the reentry of satellites such as the trajectory and velocity, as well as Earth’s atmosphere and gravity making it difficult to judge and carry out removal of debris. Also, there are social, technical, and economic systems that go into this problem, the technology to put satellites and people and spacecraft into orbit and then the technology to remove them or provide collision mapping all while needing the funds and having agreement and diplomacy between people and nations to agree on paths to address space debris. There are also many tradeoffs within this issue and there are sides to each part of it, for example with mega-constellations is the payoff of a working mega-constellation worth the amount of satellites and debris and risk that could be created in LEO by the mega-constellation being made. Space debris has been an issue since the end of the Space Race and there have been attempts to solve it, such as with Ronald Reagan and his National Space Policy, but the problem continues to grow and get worse. Lastly each nation has a different opinion and within each national there are more differing opinions all of which may define this problem differently and want to go about it a different way.

Diagram

Description automatically generatedAbove is a behavior of time graph (BOTG) that is showing the monthly effective number of objects in Earth orbit over time, the X-axis is time and goes from the year 1956-2018. The Y-axis is the number of objects, more specifically it is space debris in Earth orbit ranging from 0-16,000 pieces of debris being tracked. The graph has shown how the number of objects in Earth orbit has overall increased from 1957 when Sputnik was launched. It is slow at first and then gradually and relatively evenly increases as the Space Race transpires and the United States and Soviets perform more and more space launches. As well as those 2 countries many other nations begin to develop their own space programs and have their own satellites and space launches, furthermore, adding to the number of objects in space. There are also many jumps in the graph, each of which labeled and caused by an explosion or breakup of a satellite that produces more smaller fragments of debris in orbit, such as Spot-1 in 1986, and the bigger explosions and jumps in the graph from Fengyun-1C in 2007 and then Cosmos 2251 & Iridium 33 in 2009. There are also decreases and steady parts of the graph, both of which are due to regulation and mitigation policies by government. For example, Ronal Reagan and the National Space Policy in 1988 and the decrease in the graph after, as well as the space debris mitigation guidelines by other leading space agencies from 1996 to 2005. The long-term concerns are an increase in the amount of debris, while there is little to no decrease in the amount of space debris in LEO. This will be in part due to mega-constellations and also give way to the possibility of the Kessler Syndrome, which is where there will be a exponential increase in the amount of collisions giving way to a detrimental impact to space exploration and satellites. The hope however and the goal for resolving the problem is to eventually limit the amount of objects in Earth orbit to a lower level and eventually to an amount deemed safe enough.

**A Systems Perspective**

**Diagram, schematic

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Above is the CLD of our system and it explains how our system operates and works to perform as it does. To begin the start is our loop for satellite launches with a reinforcing loop that is promoting growth and then a carrying capacity for how many launches we can have each year which is a balancing loop. That system goes into launches which goes into our active satellites. Active and retired satellites both follow a similar route with balancing loops between the satellites and fragmentations event but also reinforcing loops between fragmentation events and damaged satellites and debris. These are each reinforcing which add to the number of debris of damaged satellites. Within that there is a wider loop between the active or retired satellites and then fragmentation events, damaged satellites, and debris, but also adding collision rate which makes the entire loop a reinforcing loop further increasing the amount of debris and damaged satellites. We also have balancing loops which remove variables from our simulation, first with debris at the bottom and that debris is leaving LEO and the simulation through orbital decay and that balancing loop. Second is with retired satellites and they are also leaving the simulation through decay as well. Lastly there are active satellites that are being intentionally deorbited through a policy. This is another balancing loop that is taking active satellites out of the simulation. This model is being supported through the dominant reinforcing loop to the left, which is providing launches to the satellites, but that decreases as the stock is distributed throughout the system over time. The loops with debris have 2 reinforcing loops with a balancing which in turn increases the amount of debris and damaged satellites which balancing and lowering the amount of retired and active satellites. The other balancing loops are all to remove things from the model with orbital decay and deorbiting.

**Modeling the System**

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This model is meant to simulate the inner workings of active, retired, and damaged satellites in low earth orbit (LEO) This model also considers space debris, yearly satellite demand and intentional deorbiting as other stocks that go on to effect the number of satellites. On the left side of the model, we have our yearly satellite demand stock with a reinforcing loop and a balancing loop that goes into the flow of launches. What this part of the model does is generate satellite launches to add to our active satellite stock, so there is a base growth of satellites launched each year with a maximum number of satellites being able to send out each year as well. We have 4 different stocks of satellites, active satellites, retired satellites, active damaged satellites, and retired damaged satellites. To start with active satellites there are 4 flows going out, which means that active satellites can do 4 things. One, they can be deorbited after their life which is shown by the “At End of Life” flow going up which also has our policy switch and deorbit compliance rate which are part of the potential solutions to remove debris from orbit. The deorbit compliance rate is the percentage of people who would follow a deorbit policy rule and when using the model changing this variable will effect how many satellites are deorbited and the effect that this has on debris fragments as well. Beyond the intentionally deorbiting stock there is another flow that is “out of orbit” which is the satellites that have been deorbited leave orbit. The flow to the right out of Active Satellites is “retired” so after a certain number of years our active satellites are then retired and become retired satellites. Retired satellites have 2 options, the first is that they naturally decay out of orbit and the second is that they are destroyed. Active and Retired Satellites can both be damaged which is shown in the bottom half of the model, these satellites are damaged and turned into damaged satellites through collisions, break-ups and ASAT explosions, which are all displayed as flows in the model. These flows will also affect our space debris fragment stock as when the satellites are damaged bits and pieces come off which are space debris. The space debris stock does 2 things, one it is going out and fragments are being deorbited or debris is staying in orbit which in turn increase the collision rate multiplier, so with more debris then there will be higher chance for collisions.

Graphical user interface

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Above is the interface, it displays all our satellites as well as the space debris fragments in orbit, as well as the satellites that are intentionally deorbited. There are 3 variables that can be changed to the right, the first is the deorbit compliance rate which is the percentage of people who follow the mandatory deorbit policy. The satellite age is how long a satellite must be in orbit before it can be deorbited. Lastly, we have the deorbit time which is changing how many satellites are in the stop intentionally deorbited and how fast once they are in that stock how many years before they naturally go out of orbit.

S**ystem Dynamics Analysis**

The question that is being followed is how we can decrease the amount of objects in LOE, we can do many things and there are many ways to tackle this problem, which are used in the simulation. The most prominent of which is with the mandatory deorbit policy, along with the deorbit compliance rate and satellite age.

The deorbit compliance rate is the percentage of people who follow the policy, and through running the simulation as we increase the compliance rate then the number of active satellites and damage active satellites goes down. For example, at only 10% of people following the policy then the total number of active satellites in 2100 was 128K and at 50% of people following the policy then the total number of active satellites was 63.3K. The amount of space debris will also decrease as the compliance rate increase, at 10% of people following then there was 2.47 million pieces of space debris, but at 50% there was half that number at 1.2 million. When increasing the compliance rate to 90% then the total active satellites is 42K and 816K space debris fragments. This was done with no other changes and only changing the compliance rate, but as that compliance rate increase then the total amount of objects and debris in LEO decrease. Along with this the number of intentionally deorbiting satellites also increased as the deorbit compliance rate increases.

Satellite age and the deorbit time are the 2 other variables that are apart of my simulation. As satellite age will increase then there will also be an increase in the total number of satellites in all categories of active, retired, and damaged. Also, with an increase to satellite age then the number of intentionally deorbited satellites will increase as well as the amount of debris fragments. The deorbit time variable will only change how many satellites are intentionally deorbiting at a time and as the deorbit time variable increases then the number of satellites in the intentionally deorbiting stock will also increase because it is taking longer for those satellites to get out of orbit.

**Conclusions**

Space debris is a continuous problem that will always be present if objects keep getting put into space, with this simulation however, solutions were able to be tested and observed. The deorbit compliance rate and the deorbit policy had the most success in lowering the amount of objects in LEO. If there is a policy that is put into place, and they enforce it with at least 50% of people following and it will drastically reduce the amount of objects in LEO. Other solutions are viable that could go down a more technical route such as the deorbit time or satellite age, if satellites can be built with shorter deorbit time or the age of satellites is increased, and the launches decreased so not as much can be put into space rather than staying in space. Within these next 10-20 years policies such as these will need to be enacted to slow the amount of objects that are in LEO and so that satellite collisions can become less probable.