Measuring Susceptibility to Kessler Syndrome of Active Satellites Through Conjunction Probability Analysis

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Background:

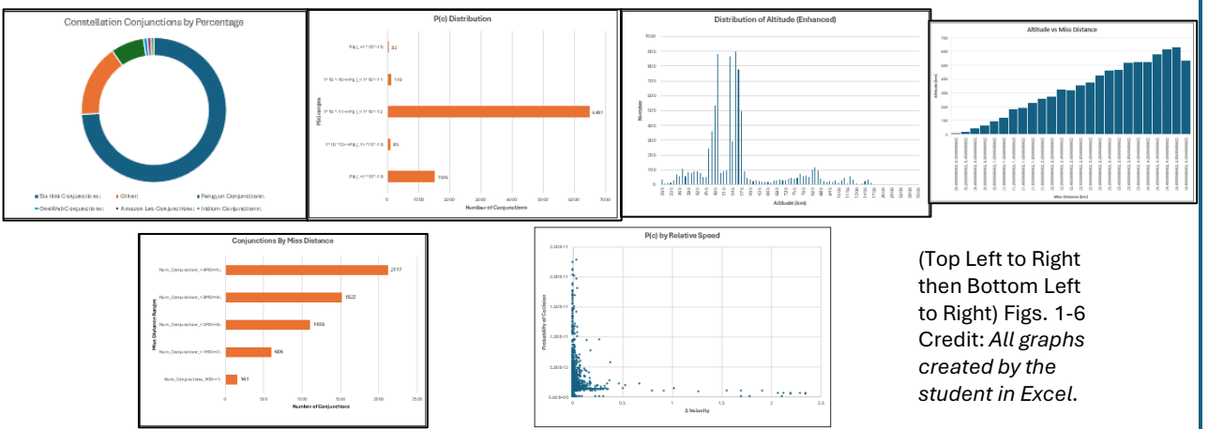
- Kessler Syndrome is a dramatic term coined by Donald Kessler and Burton Cour-Palais in 1978 for the hypothetical scenario in which large numbers of satellites collide with each other, making Lower Earth Orbit challenging or impossible to use.
- Starlink, a satellite megaconstellation planned by SpaceX to provide global access to high-quality broadband internet.
    - It plans to expand to 42,000 satellites by 2033, a truly massive number that is far beyond the current number of satellites in orbit.
- This will increase the number of close passes between satellites (called conjunctions). Each conjunction inherently has a risk of collision, which is problematic because collisions would create lots of tiny particles moving at Mach 20, which can destroy satellites themselves, including the ISS.
- Conjunction probability analysis is a way to measure this. Essentially, orbital information about the satellites allows satellites to be propagated forward in time and then compared to one another to see when they collide.
- This data is available in comprehensive form from space-track, a website managed and run by the United States Space Force.
- It is available In two-line-long packages fittingly called Two-Line Elements (TLEs). They contain the bare minimum orbital parameters needed to propagate a satellite's orbit forward in time.

Project Design:

- To perform all these tasks, I used a versatile coding language called Python, utilizing an IDE called PyCharm. Python is perfect for all-purpose uses and data analysis, befitting this task greatly. I did use some slight assistance from ChatGPT to assist in refined debugging.
- Unfortunately, the way to acquire these TLEs from sources is rather unsophisticated, as a library called *requests* mimics a user to acquire large amounts of data in a process called web scraping. This can negatively impact the performance of a website, so web scraping is highly regulated
    - Especially for government websites like space-track. I mistakenly broke a regulation and was forced to turn to a different website, called Spacebook by COMSPOC. It isn't less accurate, just not considered "official."
    - One of the things I learned from Spacebook is synthetic covariance, which is a way to create covariance matrices from TLE data, enabling increased accuracy. Normally, this covariance is assumed when not known, which decreases the accuracy of the result.
- Then, using a propagator package in Python called Simplified General Perturbations 4 (SGP4) to propagate this data forward 7 days at a resolution of 90 seconds.
- This essentially created a "grid" of locations for 30,000 satellites every 90 seconds across 7 days. I then used the KD-tree method to find when satellites passed within 5 kilometers of each other, which is a Python-friendly way to find close neighbors in point grids.
- Using the method proposed by Dr. Salvatore Alfano, I calculated the probability of collision for each conjunction, as well as keeping track of important details such as altitude and miss distance.
    - This essentially changes a double integral to a Riemann sum, which Python is much better at.
- Then, among these conjunctions, I looked for the appearance of Starlink satellites in addition to a few "control" constellations, actually finding the incidence of Starlink satellites.

Results:

- Starlink showed up in massive numbers, causing about 74.039% of conjunctions (Fig. 1)
- Despite the large number of conjunctions, the probability of collision for each was vanishingly small, around 1×10^{-12} for the average conjunction (Fig. 2).
- I also examined altitude, altitude vs miss distance, miss distance, and relative speed, among others (Figs. 3-6).



(Top Left to Right then Bottom Left to Right) Figs. 1-6 Credit: *All graphs created by the student in Excel.*

Conclusion:

- Starlink caused the overwhelming majority of collisions. Obviously, this is a problem, since they are only at a small fraction of the total number of the satellites they want to have, with only about 9,000 at the time of writing.
- Despite the large numbers of conjunctions, the risk of collisions remains very low. The actual expectation for collisions remains in extremely low orders of magnitude.
    - Of course, there are also smaller, untracked particles to contend with and any one collision would be catastrophic at such high speeds, spraying out thousands of particles into the atmosphere, which could in turn cause their own collisions.
- Starlink is aware of this issue and has outfitted their satellites with the ability to perform conjunction avoidance maneuvers if the probability of collision exceeds 3 in 10 million. It performed 144,404 of these maneuvers between December 2024 and May 2025.
- Although probabilities of collision are very low and satellites can avoid collision, collisions are not unheard of. On February 10, 2009, US satellite Iridium-33 and defunct Russian satellite Kosmos-2251 collided, creating a field of thousands of debris particles that still remains in the atmosphere today. This debris can destroy satellites that pass through it, since it is moving so fast. This risk will only rise. Clearly, some action is needed to mitigate these risks.