The Kessler Syndrome; The Invisible Hand that Guides Satellite Development and Space Regulation

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

In 1978, Astrophysicist Donald J. Kessler predicted that orbital debris collisions between tracked objects and the current debris population at the time would lead to a more hazardous operational environment by the year 2000. This debris cloud would crash into operational satellites, adding thousands of debris of different sizes into orbit around the earth; this trend exponentially increases until Low Earth Orbit (LEO) is rendered completely useless. This phenomenon is now known as the "Kessler Syndrome" (Kessler et. al, 2010). Kessler's predictions came true; by July 20, 1996, the Cerise spacecraft collided with pieces of the Ariane 5 rocket, marking the first collision between a functioning spacecraft and a piece of debris (Gregerson, 2024). By definition, debris will refer to an orbiting body with no function.

Pieces of debris pose a danger to all spacecraft in LEO. Objects ranging between 5-10 cm in size traveling at an orbital velocity of 5-10 km/s have enough kinetic energy to render a satellite useless, and objects less than a centimeter in width traveling at those velocities have the kinetic energy of a baseball thrown by a professional baseball player (Gergersen, 2024). Understanding the dangers even small debris clouds may pose, spacecraft mission engineers, large corporations such as SpaceX, and regulatory bodies have adjusted their practices to account for this growth of debris. As humans rely on satellite communications in their everyday lives, these societal entities place greater importance to not forgo satellite operational environments to upkeep for this reliance and the growth of demand.

Currently, satellites are viewed as a tool to be used in people's everyday lives for day-to-day communication without second thought. The system has grown and expanded in complexity, and it has become a pivotal part of society. These are characteristics of technological momentum; multiple stakeholders have diversified and expanded the system to the point that it has influenced the groups that design and regulate it (Johnson et al, 2021). The Kessler Syndrome is a byproduct of technological momentum; it has influenced satellite design, forced large corporations to change their practices to foster sustainability, and increased the number of government entities involved in debris mitigation. The momentum the system has gained and the reliance we have placed on it must be considered or else we will try to match the growing demand for worldwide communication, and the Kessler Syndrome will destroy the operational environment we have grown to rely on. To show how the system has accumulated this momentum by forcing different entities to work around the Kessler Syndrome, I will analyze Donald Kessler's analysis on the continuing growth of debris fields, new satellite design that accounts for a more hazardous operational environment, the shift in business practices to address the growing demand on satellite communications, and how government entities have responded to the growing orbital debris field.

Literature Review

Although there have been scholars who have looked into Donald J. Kessler's original proposition of the Kessler Syndrome, they have failed to foresee how the growth of satellite technology eventually would impact the entities that are in charge of their development and disposal. In addition, those scholars did not account for any future growth in the demand for global interconnectivity. Even if these probabilities were calculated with current situations, these numbers remain volatile as the demand for interconnectivity grows.

A paper by Misra et al. (2013) identifies the growth and advancement of satellites as well as some issues and challenges that may affect the technology. They also addressed the importance of satellite communication and the important role it plays in society, and even identified possible issues that may be encountered with government regulation, but he and his team failed to account for the possible congestion of Low Earth Orbit and the debris buildup affecting future commercial endeavors. They state that the "Satellite communication service industry has grown more rapidly than was forecasted in 1992" (Misra et al., 2013, p. 1682) showing the reliance of this technology has grown at an unforeseen rate. They list some policies and regulatory issues but specifically states that the most important to consider is "seamless interconnection of satellite, wireless, and terrestrial fibre networks," (Misra et al., 2013, p. 1685) but does not acknowledge among them proper End Of Life disposal or any future-proofing to protect the environment for any future endeavors are not priorities to be considered.

In 1996, the first in orbit collision between a piece of debris and a functioning spacecraft occurred between the Ariane Rocket and Cerise Satellite. The European Space Agency shows their predictions of any collision happening with debris or meteorites. For space debris or meteorites greater than 0.1 cm, the number of impacts per one meter squared every year would get hit 0.0095 times (Alby et al., 1997). Although these initial predictions were small, they neglected to account for any future growth of debris due to the demand for satellite communication as well as the complexity the system may continue to gain; this was a mistake many scholars at the time made in orbital collision analysis.

My analysis will consider the pitfalls that both scholars failed to address; I will consider the effect of the growing demand for satellite technology and how it affected regulatory bodies and the groups that engineered them. In addition, scholars who do research on collision probability between debris and spacecraft do not address the growth of the technology. I will emphasize the importance of considering the social impact of satellites and how it has affected practices associated with their development and regulation through technological momentum.

Conceptual Framework

My analysis of the urgency to address the Kessler Syndrome and its cascading effects draws on the Science, Technology, and Society framework of technological momentum. Utilizing this framework will allow me to explain how the growth of the satellite has forced society to alter the development of the technology to account for unforeseen conditions, as well as add space regulations to protect this technology. Technological momentum is an alternative explanation that considers a time aspect that is not considered with technological determinism and the social construction of technology. Thomas Hughes defines technological determinism as "the belief that technical forces determine social and cultural changes" whereas social construction presumes the opposite: "social and cultural forces determine technical change" (Johnson et. al, 2021, pp. 142-143). Hughes' framework of Technological Momentum does not render technology as a cause for societal change or as an effect of societal change exclusively; a complex technological system can be both the cause and the effect, and whether it is the former or the latter depends on the time aspect of the system. When a complex system gains maturity, it tends to be the one shaping society rather than society shaping it (Hughes, 1987).

The way a complex system gains its ability to control the direction of society is its momentum. As per the equation of momentum, $p = m * v$, an object with large amounts of momentum has either a large mass or a large velocity. A complex system has a large amount of mass. The way a system gains its mass are multiple entities with various interests contributing to its development. Each technical and organizational component in the system contains goals and trajectories; this is its velocity. As a system gains complexity, such as more actors contributing to the technology, it gains momentum, and begins to shape its environment (Hughes, 1987).

The Kessler Syndrome is a byproduct of the satellite's momentum. As space becomes commercialized and satellites populate LEO to meet the demand for global interconnectivity, and as nation's contend for space superiority, government agencies and regulatory bodies begin to create regulations to protect Low Earth Orbit and to protect interests in space. Drawing on Technological momentum, in the analysis that follows I begin by examining the growth of debris through Low Earth Orbit through the Kessler Syndrome, how engineers have been impacted to adapt to this new environment, expanding on the commercial growth of satellites, then finally examining how government agencies have been forced to act through an audit by NASA's Office of the Inspector General.

Analysis

There are multiple entities that contribute to the momentum of satellites with many indicators showing that the satellite has gained momentum. It is important to examine the Kessler Syndrome first before expanding upon its effects on government agencies and regulatory bodies that dictate spacecraft development. Commercial entities launching satellite constellations to meet the demand for global, high-speed connectivity have only added to the complexity of the system and also needs to be addressed. The dependence on the satellite in people's everyday lives and how this dependence affects society shows that the mass of the system has grown, indicating that each of these components have contributed to its momentum.

Kessler Syndrome and Changes in Engineering Practice

Kessler's predictions about the growing debris problem unfortunately did not account for any future growth in the demand for the satellite. In addition, changes to the ways satellites are being outfitted show that the engineers are also being affected by the buildup of debris at Low Earth Orbit. Kessler's original probabilistic models show the possible growth of the orbital debris field with varying levels of mitigation done by space mission engineers, but he has vastly underestimated the growth of the technology and society's reliance; technological momentum was not considered in the original analysis.

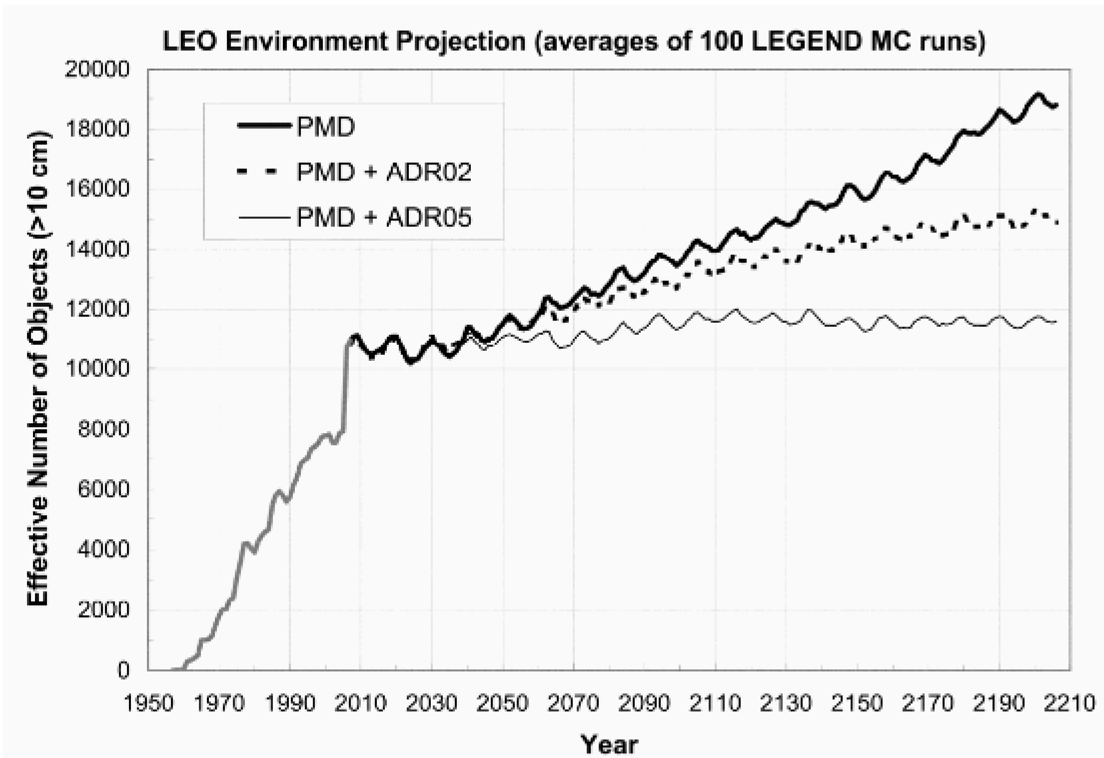

Figure 1: LEO projections for objects larger than 10 cm with varying levels of Post Mission Disposal and Active Debris Removal (Kessler et al, 2010).

According to the figure above, the left half of the graph shows the debris growth of objects greater than 10 cm starting from the 1950s to the time this paper was written in 2010. It can be seen from the original data that there is an exponential growth in the amount of debris that has been entering LEO. The right half of the graph past 2010 shows different growth rates of debris depending on the Active Debris Removal (ADR) strategy used. The solid, bold black line represents the Post Mission Disposal (PMD) compliance of 90%. This means that the upper stage or payload of a mission would fall to the atmosphere within 25 years after mission completion.

The other two lines show the 90% post mission disposal with Active Debris Removal (ADR) of 2 objects per year represented by the dashed lines, and Active Debris Removal of 5 objects per year represented by the thin black line (Kessler et al., 2010).

The most notable conclusion from the graph is the sharp growth in debris greater than 10 centimeters noted from the first part of the graph. It is imperative that PMD guidelines be followed, and even with PMD guidelines modeled with only 90% compliance, debris continues to grow, and the only way it reaches stability is with an ADR of 5 objects per year. This model created by Kessler and his team assumes that the growth strictly follows current trends, and does not account for commercial growth to meet the demands of society. Even without accounting for societal demands, the growth up until 2010 is concerning, as an object of the size noted by the graph orbiting around the earth has enough kinetic energy to render a small satellite useless and adds to the debris. Kessler et al. (2010) calls for a change in company practices to prevent debris buildup; this is a consequence of technological momentum.

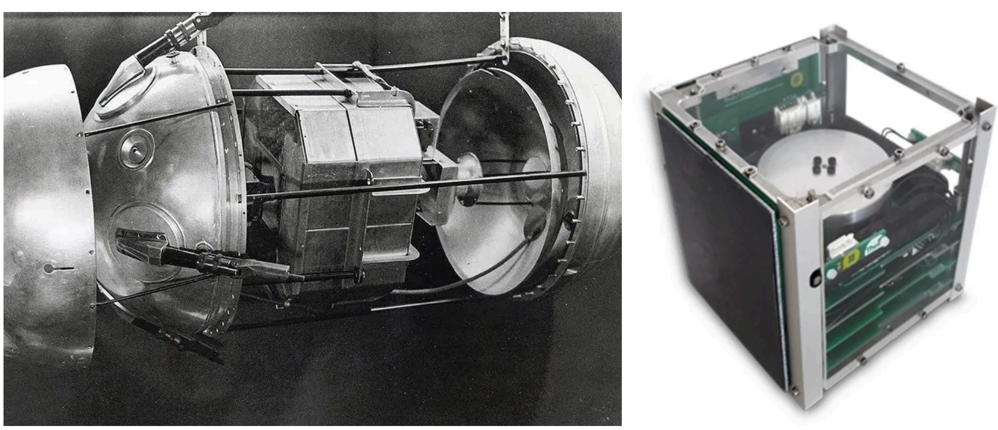

Figure 2: Exploded diagram of the Sputnik satellite shown on the left (Wallace, 2021) and a modern CubeSat with Attitude Determination and Control System (ADACS) shown on the right (González-Rodríguez et al., 2023).

Figure two depicts a modern CubeSat to the right with a dedicated Attitude Determination and Control System, shown by the wheel in the middle of the satellite. This wheel is used to reorient the spacecraft to avoid debris or change its orbital trajectory (González-Rodríguez et al., 2023). This was not present in the first satellite, Sputnik, shown on the right side of Figure 2, with the largest component being three zinc batteries used to power it shown by the box in the middle of the satellite (Wallace, 2021).

This is an example of engineers changing their practices by adding components to a satellite that can perform collision avoidance maneuvers which was not a necessity when the satellite was first introduced. This was not present in the 1950s when society was not reliant on satellite communication, and Low Earth Orbit was not as congested. The Kessler Syndrome has added to the complexity of the system through its influence on satellite design and has increased its momentum.

Acknowledgement and Response

Satellite communications are used for more than just commercial and public use, especially small satellite missions. I've argued that Technological Momentum has affected engineering practices to account for collision avoidance, but other scholars have noted the importance and the potential that building networks of small satellite constellations may have for future space endeavors.

In an analysis of small satellite capabilities by Sandau et. al. (2010), he discusses their endless applications and the advantages of their form factor being easily deployable, easily outfitted for different missions for a relatively low cost. His argument states that the importance of using more small satellite formations for low-cost missions is necessary as the world population increases. As the world population increases, lower cost missions are important to continue to upkeep for the demand of communications (Sandau et al., 2010).

While smaller satellite missions may have many benefits for them, I argue that an influx of small satellite missions would only make matters worse due to the compromises that would have to be made if they were outfitted specifically for telecommunications. For a small CubeSat, for example, the room that would have a reaction wheel for collision avoidance would have to be forsaken for heavier communication equipment. A paper by Clement Hearey (2020) states that with the number of satellites and debris in LEO, the number of collision avoidance maneuvers could reach up to 8 per hour, leading to hundreds of maneuvers a day. With the lack of a collision avoidance system in small satellites, they would be unable to avoid each other, leading to eventual collisions and thus contributing to the debris field. While it may be important to address the demand for communication as the population continues to increase, adding to the current congestion of LEO with small low cost satellites would only make the environment worse; rather, it must be accepted that larger satellites with proper end-of-life disposal protocols with the required technology for telecommunications must be used due to technological momentum changing engineering practices.

<u>Commercial Growth</u>

The Kessler Syndrome is a cause for concern as it affects different entities related to its development, but current probabilistic models fail to account for users' reliance on global, high-speed interconnectivity. To meet these demands, commercial entities continue to add to the growing congestion of Low Earth Orbit while following the bare minimum requirement for debris disposal, but the requirement to meet this demand shows that the reliance for this technology has added to the complexity of the system and increases its momentum to control the trajectory of society. The increase in momentum has forced these commercial entities to change their practices, whether it is adding to current satellite constellations, or changing the way their technology is engineered to account for the increase in orbital debris.

A press release from Iridium satellite constellation describes their findings on the demand to expand their satellite constellation. Iridium is the second largest satellite telecommunications provider behind SpaceX; they operate a satellite constellation consisting of only 66 satellites specifically placed to create a global mesh around the earth providing 24/7 coverage anywhere (Project Stardust). In a recent press release, Iridium unveils Project Stardust which aims to bring "Narrowband Internet of Things Non-Terrestrial Network service over the Iridium Network," allowing for connectivity to smartphones using existing cellular network infrastructure and the satellite constellation. They state that their demand "As of the third quarter of 2023, Iridium subscribers have grown at a 15% CAGR over the last five years, and the company serves approximately 1.7 million IoT customers today, including about 900,000 personal trackers and satellite messengers for consumer, enterprise, and government applications" (Iridium Unveils Project Stardust, 2024, para. 7). Iridium finds that the demand has grown with a 15% Cumulative Annual Growth Rate within the past 5 years, showing a very steady and reliable metric for determining the value of the returns that their product has yielded; it is safe to say that these numbers will not fluctuate as the demand continues to grow. Iridium also acknowledges their customer base as stated by the end of that statement. Earlier in the press release, they also mention that their service "supports approximately 1,300 SOS and emergency (911 or equivalent) incidents per year" (Iridium Unveils Project Stardust, 2024, para. 7). Iridium's customer base and their service providing support to emergency response systems shows the importance of their service to different facets of society. Coupling this with their growth continuously increasing with Project Stardust will only bolster the demand for satellites as it continues to cement itself as a staple in every day operations of different parts of society. Project Stardust emphasizes why it is important to mitigate the effects of the Kessler Syndrome as many day-to-day functions and emergency personnel rely on this service.

Another commercial entity that has gained considerable growth and now takes up half of the United States' tracked satellites orbiting the earth is SpaceX with their Starlink constellation network. The Starlink constellation consists of more than 5,000 operational satellites in orbit as of February 2024 (Pultarova et al., 2022). The purpose of this satellite constellation is to bring internet connectivity to every part of the world as well as support SpaceX's vision of going to Mars. SpaceX's satellite constellation has sparked some controversy regarding orbital debris buildup, collision mitigation, and satellite end-of-life disposal especially after the FCC's approval to add 12,000 satellites into orbit (Heary, 2020).

However, SpaceX made a public statement regarding their practices in their recent "Commitment to Space Sustainability" in February 2024. They discuss their Proactive Controlled Deorbit system, and how their satellites are deorbited before they are non-maneuverable (SpaceX, 2024). Notably, in this statement, SpaceX "encourages all satellite owners and operators to safely de-orbit satellites before they become non-maneuverable. Just as importantly, even as we lower and de-orbit satellites, Starlink's customer experience will not be impacted" (SpaceX, 2024, para. 4). SpaceX does more than just explain the practices they have adapted, but also try to recommend to all other satellite operators the importance of proactive de-orbiting, effectively trying to change the practices of other businesses in space-based telecommunications. To emphasize the reliance on SpaceX's satellite constellation, they emphasize at the end of that statement that their customers will not be impacted, ultimately highlighting their biggest priority, which is meeting the demand for their service.

<u>Government Bodies and Space Regulations</u>

The Kessler Syndrome not only has affected engineering and business practices, but it has spread to the actions of different government agencies. Satellites have become a cornerstone in communication, and have forced government agencies, such as NASA and the FCC, to take action and produce new regulations to address this issue. Orbital debris mitigation has stretched to multiple government entities in response to the Kessler Syndrome, contributing to the complexity of the system and increasing momentum.

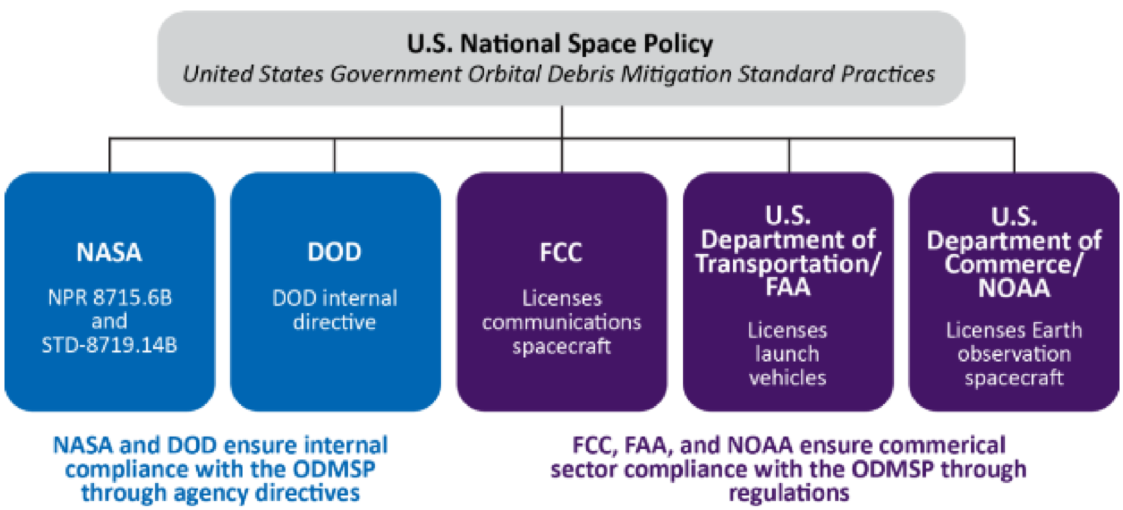

Figure 3: Government entities dictating space regulations (Office of the Inspector General, 2021).

NASA's Office of the Inspector General did an internal audit of the efforts NASA has done for orbital debris mitigation. In their audit, they also discussed the key government agencies involved in making and enforcing space regulations that commercial space entities in the U.S. must follow for launch vehicles. The Department of Defense notifies NASA and other entities of any impending collisions, but LEO has become so congested that it has not been able to keep up with private-sector space activities. The Federal Communications Commision, Department of Transportation, Federal Aviation Administration, Department of Commerce, and National Atmospheric and Oceanic Administration have been in charge of private sector regulation of space activity. These were only the national entities. In addition to these, international cooperation has been necessitated, as a whole organization, the Inter-Agency Debris Coordination Committee consisting of 13 countries have joined to agree on regulations to be followed by government and commercial spacecraft (Office of the Inspector General, 2020).

Another facet of society that has been impacted by the growth of the Kessler Syndrome has been government entities. All of these government agencies have been involved in making and enforcing regulations regarding satellite design, manufacturing, launching, and space mission engineering to prevent the continuous buildup of space debris within LEO. One of the key parts of a system gaining momentum is the complexity of the system (Hughes, 1987). To have a mission approved for private or personal use, it has to undergo approval across five United States federal organizations, as well as compliance with international regulations. The satellite has manipulated the environment through these entities due to the number of organizations involved, and it has gained velocity through the sheer number of organizations determining its trajectory.

Conclusion

Although the satellite has always been viewed as a communications technology prevalent in everyday lives that must be expanded, it has grown to become a complex system that has become pivotal in society. The Kessler Syndrome has grown as a byproduct of the momentum gained by this system; first, different entities have influenced the trajectory of this technology, but as the system matured, the practices of these entities are now being affected by the technology they originally developed. It has gained its momentum by changing how engineers design satellites, by forcing large corporations to change their practices to adapt to a new space environment, and by increasing the complexity of the system through the number of government actors and international entities that have been involved. Accounting for the control that the satellite has gained over society through technological momentum must be considered, or else we will continue to blindly rely on it, expand the system to meet the growing demand, and only add to the control it has gained over society. This vicious cycle perpetuates until the Kessler Syndrome grows to destroy the operational environment we rely on.

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