Orbital Debris; Problems, Solutions, and Impacts on the Design and Implementation of Orbital Infrastructure.

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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

As technology surrounding space has improved over the last seventy years, modern life has also become more reliant on systems situated in space. Satellite internet, imaging, and GPS among many other technologies in space have become intertwined in everyday life, so much so that a disruption of these systems would be devastating, bordering on catastrophic to the modern world. One of the theorized risks to humanity's growing orbital infrastructure is a phenomenon known as Kessler Syndrome, theorized by Donald J. Kessler (Kessler, 1978). Kessler Syndrome posits that the ever increasing number of orbital objects in earth's orbit may reach a critical mass and cause a chain reaction-like effect that could disrupt the majority of orbital infrastructure operations in low earth orbit (LEO).

Kessler's paper concluded that the number of orbital debris present in 2001 meant that an equilibrium was unlikely to be reached in much of LEO, and many regions were in an unstable state, meaning a drastic growth in orbital debris was likely (Kessler & Anz-Meador, 2001). The number of orbital objects greater than 10cm in diameter has more than quadrupled since the release of Kessler's paper, therefore the current state of LEO is significantly more unstable than in the past. In recent years, the rate of satellite launches has grown exponentially from previous trends, in large part due to the advent of Starlink, a Satellite constellation system, designed to give 24/7 satellite internet coverage to the entire world (Bongers & Torres, 2023). It is reasonable to assume that this type of orbital infrastructure proliferation will only become more prevalent as the demand increases and the technology improves.

In the event that Kessler's Syndrome becomes a reality, it is likely that all LEO infrastructure will be put at risk of collision with orbital objects, making their operation uneconomical and generally infeasible. It will also greatly impair the ability for any types of launches into orbit, essentially locking humanity out of any operations in space until the orbital debris can be cleared. Currently, there is little risk posed by orbital debris, and collisions are few and far between, with only a few recorded cases in the history of satellite operation (Liou & Johnson, 2006). At the current rate of growth however, this situation is expected to grow increasingly unstable, meaning that there may be less time to act than we hope. In Kessler's paper written about this phenomena in 2001, he stated that "The results strongly support the implementation of current policy to limit the accumulation of intact objects in Earth orbit and suggest that more actions may be required" (Kessler & Anz-Meador, 2001). Despite the worry that has been generated by this paper and others on similar topics, very little has been done to prevent the accumulations of orbital infrastructure, as few countries have regulations mandating the safe use and disposal of satellites past their lifetime (United Nations, 2010). Overall, the accumulations of orbital debris and the possible advent of the Kessler Phenomena appears to be one the largest problems facing the rapidly developing industry of orbital infrastructure, and little has been done to stop it. If humanity is to continue space based operations, it is pertinent that actions are taken quickly to stem the growth of orbital debris, and protect the industry from total collapse. To this end, this paper will quantify the current and projected impacts of orbital debris as well as the effectiveness of current preventative techniques to inform a plan of action to prevent the long-term deterioration of orbital infrastructure

Background and Significance

Kessler Syndrome is motivated by the mechanics of orbital collisions, where, due to the collisions taking place in space with nothing to slow down orbital debris, hundreds of fragments can be released at speeds ranging from 5-10 km/s (Kessler & Anz-Meador, 2001). In order to estimate the relationship between orbital object collisions and orbital debris generation, Kessler analyzed a test collision between a 850 kg satellite and a 16 kg projectile occurring at roughly 7 km/s in September of 1985. This event created 285 cataloged fragments and was used to predict fragment generation, fragment decay, and mass ratio required for catastrophic collisions (The ratio of the mass of the two orbital objects that are colliding). Using models created from this data, Kessler was able to predict regions of specific interest due to their long time to decay, and found that the region between 900-1000 km altitude, the 'best case' environment, would reach equilibrium in two thousand years assuming a constant number of orbital objects (Kessler & Anz-Meador, 2001). If instead of the best case environment, one assumed an increase in orbital objects according to past rates of satellite launches, Kessler's model predicted that the region between 800 and 970 km would never reach equilibrium, and always would remain unstable(Kessler & Anz-Meador, 2001). The process of the Earth's orbit becoming unusable due to orbital debris is likely to be slow and gradual, but the presence of an unstable environment means that the number of debris in such a region will grow exponentially.

In 2010, Kessler expanded on the implications of his previous work, and confirmed that the trends he had predicted 10 years earlier had been reasonably accurate (Kessler & Johnson, 2010). Through showing that both the rate of increase of orbital objects and the rate of collisions were increasing, Kessler determined that controlling the growth of orbital debris in LEO was more important than ever, and that regulations and preventative measures needed to be overhauled and strictly adhered to. Kessler recommended an approach to solving this problem that involved 90% compliance with orbital debris prevention guidelines, selective retrieval of possible future debris sources, a more focused collision avoidance policy, and active removal of current debris. Unfortunately, these policies have been scarcely adopted, with only a few countries having implemented orbital debris prevention guidelines, and selective removal technology still being in the early stages of development, much less widespread use (Barry, 2022).

A paper released in 2009 by Andrew M. Bradley, modeled the Kessler Phenomena using differential methods, and came to a conclusion similar to Kessler's: "It appears that if full compliance of the 25-yr spacecraft deorbiting guidelines can be achieved within the next few decades and no ASATs (Anti-Satellite Weaponry Tests) are used or tested in the future, then the lifetime risk from space debris in the SOI may be sustainable at a tolerable level" (Bradley & Wein, 2009). Bradley also completes an economic analysis in this paper, predicting that with current launch rates and deorbit costs, it would take around a thousand years for the costs to rival the launch of a single defense satellite. Bradley goes on to conclude that "It seems improbable that a future technology will be able to clean up space for less cost than launching a single defense spacecraft", suggesting that tightening regulation or fees for bad launch and orbit protocols, and taking initiative now to actively deorbit satellites before they become orbital debris will pay dividends in the long run.

Currently, nowhere near 90% of satellites launched have followed regulations in recent years, as the ESA (European Space Agency) estimates that only 15-30% of non naturally compliant satellite launches have adhered to their guidelines (ESA, 2023). Rocket launches have instead been much more compliant, as the ESA estimates that 60-80% of rockets have adhered to their guidelines within the last 10 years. In 2013, Nodir Adilov developed a method to model the private incentives to launch satellites and adhere to space debris mitigation guidelines and active debris removal practices (Adilov et al., 2018). In his paper, Adilov determines that voluntary guidelines prove ineffective to promote good practice concerning orbital infrastructure, and that competitive firms will typically choose the least costly and generally least effective mitigation technology, therefore generating more debris because it carries lower costs for themselves. Adilov also acknowledges that active debris removal technology is "...pre-emergent and costly" and that "Since active debris removal is retrospective, nations that have created the majority of extant debris, the United States, Russia, and China, might provide funding commensurate with created debris". Adilov also recommends a tax on launches to provide a straightforward solution to space debris creation, and future research into remediation technology and policies.

Overall, these studies all echo the same idea - that orbital debris are a growing problem, and that not enough work is being done to mitigate the risks that they may cause in the future. In the next section of the paper, I will examine the analytical framework through which various actors interact with this problem, and recommend courses of action to solve this issue before the effects become catastrophic.

Methodology

In order to assess the question of the level of action needed in solving the growing issue of orbital debris, I approached this issue both from a technical perspective, analyzing the various scientific views on the issue, as well as through a sociotechnical lens, determining the key players, their respective motivations, and an analytical framework from which to decide the best course of action for remediation. The technical perspective was widely discussed in the background section, and thus this section will focus on the sociotechnical side of the problem. To begin to analyze this aspect of the issue, one must first determine the relevant players and their motivations. In regards to the problem of the proliferation of orbital debris, I have determined three main players; Private Corporations, Government Organizations, and the General Public. Private Interest Corporations typically means entities that act outside of government funding, operating off of contributions from the public or private investments. Examples include companies such as SpaceX, Virgin Galactic, and Blue Origin, as well as some government contracted companies such as Lockheed Martin and Raytheon. While a number of these entities are still partially beholden to funding from governments, the majority of their capital comes from the goods and services that they market. This means that while some of their income may be tied to governments that import regulations and guidelines, they are mostly beholden to the will of the public, and thus if the public continues to fund their activities in spite of malpractice, regulation ends up mattering less to these corporations than public opinion. Government Organizations, as the name would have you believe, are chiefly beholden to the government, and through further extrapolation, the will of the people. These organizations are more chiefly governed by the ideals of the people instead of the throes of capitalism that loosely mimic the short term will of the market. In practice, this means that these corporations will typically be at the leading edge of both the creation of regulations and the adherence to said regulations that lead to more longevity of the industry. Finally, the general public is the actor that tends to absorb the ramifications of any long term actions of a given industry, whether they be positive or negative. There has been a lack of regard for this aspect of the orbital infrastructure industry, likely due to the technological momentum that has built up while concerns for orbital debris were not a large part of the discussion in orbital proliferation. Currently, almost all of the action taken to prevent the growth of orbital debris comes from personal concern for the longevity of LEO, which is not a common stance among companies currently interacting with earth's orbit. Implementing a solution to this problem before the ramifications are serious will involve all of these players implementing strategies that promote ethics of care; preserving the health of LEO by foregoing short term gain for the long term health of the industry.

Literature review

In order to determine a recommended course of action, I continued my exploration of the academic literature on the topic of the effect of and proliferation of orbital debris surrounding earth. I focused on three key areas in my research, orbital debris propagation and the likelihood of a critical chain reaction event occurring, the economics of orbital debris and their removal/prevention, and the effectiveness and development of orbital debris removal technologies.

I will first examine projections for the landscape of orbital debris in LEO, which, as discussed previously, is both the most active regions for satellites, and the most important due to it being the location of most sun-synchronous orbits. In previous sections the basis for concern of orbital debris was established, mainly citing research from Kessler dating back to 1978 (Kessler, 1978). To better understand the current landscape of LEO, more recent papers were examined to get a more complete perspective of the problem. Conclusions on the current state of LEO have been somewhat conflicted over the past few years. A paper by J.C. Liou published in 2013 on the stability of the future LEO environment used data from six major space agencies (ASI, ESA, ISRO, JAXA, NASA, and UKSA) to simulate future launch environments, and found that with 90% implementation of mitigation measures, LEO debris populations were expected to grow by 30% in the next 200 years (Liou et al., 2013). Liou also noted that the 90% compliance assumption was much higher than reality, and that the population growth of debris in LEO was likely to be far worse than the study predicted, and that remediation will "... Likely require a tremendous amount of resources and international cooperation". A more recent paper written by Hugh G. Lewis published in 2020 examined the growth of orbital debris in earth's orbit following the widespread adoption of remedial and preventive measures known as the 25-year rule, a plan for post-mission disposal (PMD) of satellites (Lewis, 2020). Lewis found that despite widespread adoption of the aforementioned measure and relatively low collision rate, the debris population in earth's orbit is growing at an accelerating rate, and that the PMD measures that were enacted have had much lower significance than previously thought, and that the disposal orbits were ineffective as removing orbital debris in a timely manner. Lewis concluded that "... Additional, and possibly new, measures to mitigate the effect of orbital debris may be needed". Another paper published in 2020, written by V.V. Adushkin, specifically examined the effect of the small orbital debris on space activities. Adushkin examined data of orbital debris in near earth space (NES) and found that these small orbital debris were traveling at speeds high enough to cause orbital debris generating collisions, and that the growth of these small orbital debris was "... Steadily approaching the onset of Kessler's cascade syndrome" (Adushkin et al., 2020).

Economic projections of orbital debris damage, removal, and prevention, began to be studied more recently than the general issue of orbital debris, and thus there is somewhat less research that has been done on this specific effect of orbital debris. One of the more recent papers on this topic was published by Bongers in 2023, which examines a model created to study the effects of a decline in launch cost and increasing number of satellites in LEO in relation to the number of orbital debris in LEO. Bongers establishes an 'Economic Kessler threshold' which gives a rough estimate of the number of satellites in orbit that would make it likely for any further launches to be a net negative economically. The model used in the paper predicted an economic Kessler threshold of roughly 72,000 satellites in earth's orbit, a number that is lower than the physical Kessler threshold, and also larger than the number of satellites currently in orbit, but a number that Bongers predicts will be reached quite soon given the increasing prevalence of satellite constellations such as Starlink (Bongers & Torres, 2023). The previously mentioned model created by Nodir Adilov analyzed a similar phenomena to the one explored by Bongers, and came to a similar conclusion, that the economic factors related to orbital debris would cause launches to become infeasible before a critical Kessler threshold is reached. A more recent paper by Adilov delved deeper into this concept, studying the economical relationship between orbital debris accumulation, mitigation, and remediation. This paper specifically discussed the negative externalities associated with orbital debris generation, that is to say that any satellite launched inherently imposes costs on current satellites and future satellite launches. Using this framework and model, Adilov projected the effectiveness of various remedial techniques such as launch taxes, various debris removal methods, and various compliance levels with launch guidelines. Adilov's model predicted a net reduction in orbital debris only in cases of active debris removal combined with compliance with launch guidelines (Adilov et al., 2020).

The final area I examined was the effectiveness of current active debris removal (ADR) technology and the progression of said research. A paper published in 2009 by Liou examined the projections of orbital debris populations given varied removal rates in order to construct a guideline for required technological efficacy. Liou simulated four scenarios, all with starting debris projections for the year 2020 with varied removal levels of 0, 5, 10, and 20 per year. The model predicted net negative growth in orbital debris only with ADR solutions that could remove more than 10 orbital objects per year, and it must be remembered that this paper used debris growth predictions from 2009, which have proven to be conservative in regard to current orbital debris generation rates (Liou, 2009). Satomi Kawamoto wrote two papers, in 2018 and 2020, delving into the specifics of ADR technology and PMD regulations as well as the overall effect of these methods on the population of orbital debris. Kawamoto's 2018 paper focused on PMD regulations, and found that in order to suppress long term increase in orbital debris in LEO it was important to disperse operational orbits, increase PMD compliance rates, commence PMD on current satellites, and begin collision avoidance measures (CAM) on all satellites (Kawamoto et al., 2018). Kawamoto's 2020 paper examined further situations than his previous paper, including the addition of ADR into his model. Kawamoto found that tether and sail ADR technologies were effective at reducing the overall chance of collisions for a given orbital object, as well as decreasing the severity (number of fragments generated) of a collision if one did occur (Kawamoto et al., 2020). Kawamoto also analyzed situations involving satellite constellations, and found that this greatly increased the risk of collisions for the altitude that it was deployed in, up to 100% collision rate within certain altitude bands. A recent NASA study conducted in 2023 performed a cost benefit analysis of orbital debris remediation, and noted two technologies are particularly promising for debris removal purposes: laser and rocket nudging (Colvin et al., 2023). NASA established a cost-benefit curve for which any technology implemented that was under the curve would have a net saving in the long run, in terms of cost associated with removal of debris or replacement in case of collisions.This analysis determined that ground and space based laser removal were the most likely to be cost effective for both large and small debris removal. NASA also found that the most cost effective overall methods for risk mitigation was removal of small orbital debris, and nudging of larger orbital debris in near time scales as opposed to longer term techniques such as orbital debris sweepers or recycling.

Results and Discussion

Through the literature review conducted in the previous section, it is evident that the body of research that has been conducted on the issue of orbital debris is conclusive at least in one regard - that not enough is being currently done to prevent the growing issue of orbital debris and eventually a critical mass leading to widespread occurrence of the Kessler effect. The first section of papers examined in the previous section all generally concluded that under current conditions, the orbital debris population was expected to grow to a critical level given enough time, and that the current level of remedial measures was insufficient to prevent such growth. The exact mechanisms of this growth are somewhat contested, as some researchers think that the orbital debris population will reach critical levels within 30 years of growth, while others think it will take 200 years. Much of the dispute on this issue comes from varied predictions on uptake of PMD and ADR measures, with some researchers predicting current levels of remediative measures, while others predict large increases in these policies.

This brings us to the second topic of literature review, the economics of orbital debris, and the motivation of private and public actors to engage in any remedial measures. The papers reviewed in this section all generally agree that the 'Economic Kessler threshold' will occur before a critical physical Kessler threshold is reached. That is to say that the economic effects of orbital debris collisions will make the launch and operation of satellites in earth's orbit infeasible before a critical chain reaction occurs.. In previous sections the motivation of these actors was discussed in detail, and while the government actors were motivated generally by the will of the people they govern, which encourages the preservation of orbital infrastructure, private actors are instead beholden to the profits that can be gained through the operation of orbital infrastructure. In this case, the economic Kessler threshold means that it is in the best interest of all actors involved to preserve the health of the orbital environment, either to maintain the technological benefits or the profits produced by these technologies.

For the action that can be taken in order to enact the interests of these actors, the papers in the literature review were generally concluding the same ideas. All of these papers emphasized the importance of passive remediation such as PMD, better launch/satellite design, and complete compliance with satellite launch and operation guidelines. These orbital debris prevention methods all have much lower cost to implement as compared to ADR technology, while still providing significant benefit. Disagreement arises when considering the implementation of ADR technology. Some researchers believe that passive prevention methods are sufficient to maintain economic and operational viability to space infrastructure in the long run, while others believe that they will merely delay the inevitable without further reduction through the use of ADR. It seems that the prevailing view is that ADR will be needed to prevent onset of the Kessler effect, mostly due to the continuing increase in rate of satellite launches, especially concerning the increase in constellation satellite launches, which appear to pose the most risk to the orbital environment. The conclusion from these authors is that at the very least the actors in this situation should enact the least costly and easiest to implement remedial techniques, passive methods including PMD and compliance with launch/operation guidelines. These methods pay for themselves in a very short amount of time, and provide much more time to develop better ADR technology before a critical mass of debris is reached in orbit. As mentioned in the economic discussion, there may be an issue with enforcing the widespread implementation of these policies as there is benefit to the private sector actors involved to refrain from enacting said policies in favor of short sighted gain.

Conclusion

Overall, orbital debris proliferation and the Kessler effect is a growing problem for orbital infrastructure that could threaten the entire ecosystem of the industry. Research is generally conclusive though, that this issue is solvable given the right amount of effort in the right places. Due to conflicting priorities from the actors involved in this industry, prioritizing profits versus the continued operation of orbital infrastructure and the benefits that it provides to humanity, a varied approach to remediation techniques is required. In order to ensure that all parties engage as required with preventative measures, legislation should be enacted in order to enforce cooperation with the best practice guidelines for the launch and operation of orbital infrastructure. Even though the economic papers agree that it is in the long term economic interest of all involved parties to engage in remedial measures, some companies may prioritize short term financial gain over long term industry health, and thus legislation will help to ensure that all actors are participating as required.

Though passive remedial measures will at least delay the issue of orbital debris for a long time, effort still needs to be put into ADR technological development and eventually deployment. Though some authors believe that passive mitigation will be sufficient, I believe that due to the ever increasing number of orbital launches and objects, especially the increasing prevalence of constellation satellites, ADR technology will be needed to prevent a long term proliferation of orbital debris, and preserve the industry into the foreseeable future. To this end, there should be continued and increased funding into these technologies to ensure that when they are needed, they will be available to use, and this technology should be put into use as soon as possible to begin to diminish the orbital debris population. If all of these methods can be put to practice within a reasonable amount of time, the industry of orbital infrastructure can be relatively easily preserved and maintained for current and future generations. All that is required is foresight and forward thinking, to ensure that the Kessler effect doesn't get out of hand due to a prioritization of short term profits over long term health.

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