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The Cost of Clean Space- A Study of the Additional Fuel Costs of Launching Above Low Earth Orbit

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By

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Abstract:

Ever since the launch of Sputnik in 1957, humans have put over 40,000 pieces of debris into orbit around the Earth. In particular, most launches and debris tends to go to either Low Earth Orbit (LEO), or Geosynchronous Earth Orbit (GEO). While GEO has some regulations on its use, there are limited regulations for the use of LEO. Accumulated debris in LEO jeopardizes the future utility of space. So far, various measures for the mitigation and management of debris in LEO have been proposed. This paper looks to establish a baseline cost of clean space in LEO against which other debris management policies can be compared. By launching to MEO instead of LEO, an upper bound cost of $22.15 million would needed between now and 2050, by which time about one third of all the debris pieces in LEO would have decayed into the upper atmosphere. Though such a policy is not likely to be implemented, and downright impossible to carry out for microsatellites, the cost study should serve as a baseline for other proposed policies to keep LEO relatively clear of debris and safe for continued human use.

Introduction:

The Common Heritage Question:

Humans have claimed land since the beginning of humanity and today nearly every speck of land down to the tiniest island and reef is claimed by around 200 sovereign nations. In 1857, the Copenhagen Convention made the Danish Straits connecting the North and Baltic Seas accessible to all military and commercial shipping. This would set a precedent that lead to the modern notion of International Waters. The last major international agreement governing territory on Earth would come in 1959 with the Antarctic Treaty (US Department of State, 1959). This treaty would preserve Antarctica for nature and prohibit weapons testing and mining on the continent. Antarctica would be lumped in with International waters and the ocean floor under the category of the “common heritage of mankind”.

The idea behind the “common heritage” is to preserve these areas and make them available for future generations, but a curious byproduct of this idea is that everyone owns these areas and nobody owns them simultaneously. This nebulous arrangement so far suits Antarctica, which has no intrinsic value other than for scientific research under the current treaty. Antarctica also has clearer rules about who is allowed and what they can leave behind. Only scientists and tourists are allowed and they cannot leave anything, including human waste, behind.

Since the Copenhagen convention, treaties regarding the use and access of International Waters have gone smoothly. Access to International Waters is vital for any nation, putting particular stress on landlocked countries. The International Chamber of Shipping estimates that 90% of all global trade is conducted by sea (Shipping and World Trade Overview, 2017). In 1879, Chile seized a corridor of the Pacific Ocean from Bolivia in war, making Bolivia landlocked. Diplomatic relations between the two nations have been sour ever since. Bolivia recently staged a protest by stretching a 200 km flag through to the Pacific Ocean to demand access to maritime shipping (Colossal Flag Protest, 2018). Clearly, International Shipping is vital to any nation’s security and prosperity and being “landlocked” is a decided disadvantage.

Space has nearly unlimited advantages in both areas as well and perhaps being “spacelocked” will be crippling to national development in the future. Countries that lack their own space programs or land near the equator will be at a competitive disadvantage in the near future as spacefaring nations look to expand human settlement, build satellite infrastructure, and mine for metals and other mineral resources on nearby planets and asteroids. When Jules Verne published *From Earth to the Moon* in 1865, he assumed that the first moon launch would take place in Tampa, Florida; the actual first moon launch came barely 100 years and only 120 miles away (Verne, 1865). He was able to predict this launch as well as he did because launches near the equator require less fuel to reach outer space because they are moving at faster relative speeds due the rotation of the Earth. By guessing that the United States would carry out the first lunar landing, Verne assumed the space center would be at the place closest to the equator and thus very precisely predicted the event. Even today, countries look to launch from the places in their territory or sphere of influence closest to the equator: the United States from Florida and Southern California, Europe from French Guyana in South America, and Russia from Kazakhstan.

But access to equatorial space centers is not the most threatening to space access in the future. Manmade orbital space debris could possibly make future space travel exceedingly difficult. Outer space is the newest frontier in the question of common heritage, falling under the same category as International Waters and Antarctica. It is governed under the same common heritage nomenclature, but it has very little similarity with the other domains. Space is currently integral to modern life and space agencies and companies routinely leave all kinds of debris behind, which could jeopardize making space useful for future generations. And space is critically useful to all sorts of stakeholders. National security satellites keep the leading nations of the world safe; Earth observation satellites and space telescopes push the boundaries of science while private companies are beginning to develop space for vast commercial and communications projects. Despite this immense value, space is currently devoid of major global policies to govern it.

The year 1957 marked the first time a treaty was proposed to regulate outer space. Even before the launch of Sputnik, the first artificial satellite in space, the Outer Space Treaty outlined the use of space for peaceful purposes only (Outer Space Treaty, 1957). But other than outlining space as a region free from weapons testing and military bases, there are no provisions for how space should be managed. In 1967, another Outer Space Treaty tried and failed to set up a consistent legal definition for space debris and establish liability for its creation (Outer Space Treaty, 2018). Since 1957, the number of spacefaring nations has jumped from just the United States and the Soviet Union to nearly 20 nations as well as private companies like SpaceX and Virgin Galactic (MacDonald, 2014). With so many competing peaceful interests, a Cold War weapons agreement among two superpowers seems wholly inadequate on its own for the future management of space. As more entities become spacefaring and as the uses for space continue to expand, better definitions and management of orbits will need to be established.

The Problem of Space Debris:

Since Sputnik, orbits around Earth have been filling up with all types of objects, from satellites and launch vehicles, to debris. Over 42,000 man-made objects have been tracked in orbit since 1957 (see Figure 1 below). This debris is usually small, but the term covers everything from a loose screw to a spent rocket booster (Wilson, 2004). Each launch adds debris to orbit which can endanger other spacecraft and satellites with impacts at high velocities. Although the rate of debris addition has slowed in recent years thanks to better orbit planning and satellite infrastructure, an increasing number of launches and competing interests makes

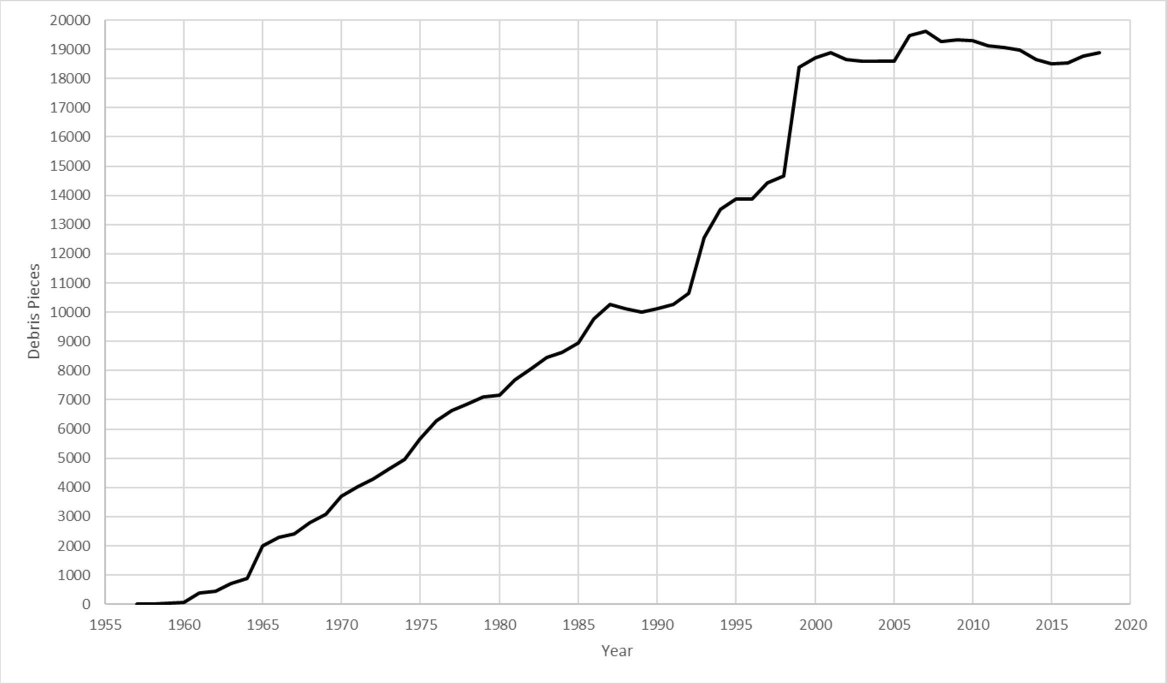


Figure 1: Total number of man-made objects in all orbits by year (Space-Track, 2018)

orbital debris a growing concern. More concerning is if debris is not properly managed, it could reach a threshold where debris collisions spawn off each other in a chain reaction, making a cloud of debris and causing space to be unusable.

Most satellites and all human space flights are launched to Low Earth Orbit (LEO), the region extending from the upper atmosphere at 500 km to about 2000 km. Most missions, including all manned missions, are launched to this region because it is the most economical to reach. Therefore, most orbital debris is concentrated in this zone as well.

Geosynchronous Earth Orbit (GEO) is a narrow band around 42,000 km which is also of interest to debris studies because of its unique orbital period of exactly one day, allowing satellites to appear to hover in a fixed position in the sky. Because it is such a narrow region and so highly prized for observation and communication, the problem of space debris is greatly exacerbated. Debris can stay in GEO for centuries at a time, whereas the lowest orbits in LEO can decay into the upper atmosphere in less than a decade. To prevent this coveted band from being overtaken by debris, the International Telecommunications Union set up strict debris mitigation guidelines in 1960. (Zoller, 2007). A key stipulation of this agreement requires prospective satellites to be registered to a specific location in GEO through the International Telecommunications Union. This registration entitles the satellite to be in its particular spot for a fixed period of time and only that time. Afterwards, it is required to vacate the spot for new use, usually by moving to a higher “graveyard” orbit that makes way for new satellites. Medium Earth Orbit (MEO) is the region between LEO and GEO which is not overly populated or of great concern for debris management. By contrast, most debris and active satellites currently in orbit are in LEO which has no universal orbital management system like GEO has under the International Telecommunications Union. The lack of regulations in LEO coupled with the sheer number of satellites and other pieces of space debris make it a policy arena that is worth investigating. Because of this, LEO will be the area of focus for this paper.

The only current regulations in LEO come from the Federal Communications Commission (FCC) in the United States. The only regulation states that “applicants requesting authority to launch and operate a space station, or requesting access to the U.S. market for a non-U.S. licensed space station, [are required to] disclose plans to mitigate the creation and effects of orbital debris [to the FCC]" (United States, 2013). This regulation only applies to communications satellites that are either launched by the United States or might service markets in the United States. Exactly what mitigation plans are acceptable to the FCC can be loose as well, with some applicants only using sturdy satellite construction to mitigate debris while others have more detailed end of life plans for their satellites. The fact that the FCC is starting to take control of the hazards of orbital debris is reassuring, but not enough to solve the problem of orbital debris on its own.

Growing Concern Around Orbital Debris:

In 2007, China tested an antisatellite weapon system which created a large cloud of debris and heightened awareness both about weapons testing and debris management in space. Debris management in LEO was of particular concern. Then in 2009, the first collision between satellites suggested that debris and orbital management was an issue that needed attention. While these are major collisions generating thousands of pieces of new debris, studies indicate that numerous collisions involving 1 cm diameter or greater particles are already problematic (Krisko, 2007). But exactly how grave this concern is a matter of debate.

One matter that could greatly increase the issue of orbital debris is miniaturized satellites. For example, new research satellites known as CubeSats are constructed from multiple cubes that are 10 cm on a side. Due to advances in technologies from thin solar cells to higher performance batteries, the essential components of a satellite have been scaled down to this size. Previous satellites might have needed to be the size of a small car. This means that where launches in the past might have just one or two large satellites, now it is possible to launch dozens of CubeSats in addition to the major payloads with each mission. Rapidly growing communication technology signals that constellations of CubeSats might replace large satellite infrastructure in the near future (Miles, 2016). But building new satellite infrastructure using swarms of CubeSats exacerbates the issue of orbital debris and makes it difficult to discern the difference between a piece of debris and a functioning satellite from the ground.

Equally debatable as the scale of the debris problem is what policy measures should be pursued to help mitigate this problem. One general practice is known as the “25 year rule”, where satellite orbits are designed to decay back into the atmosphere after 25 years. This is not a policy that is enforced, but is recognized as an industry standard. It could be effective, as long as the rate of launches does not overtake the rate of decay. Merely improving satellite design can also help mitigate accidental creation of debris. A more aggressive plan is active removal. Active removal missions involve sending spacecraft into orbit which grab pieces of orbital debris and then drag them down to the upper atmosphere where they can burn up. Lastly, space is not only hugely valuable economically, but is vital to the national security of any spacefaring nation. Just like climate change, it is in the interest of all spacefaring nations to help clean up space and yet they may not be willing to limit their own number of launches or participate in mitigation strategies. This situation of competing self-interests could effectively block any new international agreements on orbital management. The similarities to climate change end with the analogy of prisoner's dilemma in global politics, however, as space debris burning up in the atmosphere poses no more environmental risk then the meteorites that burn up in the atmosphere every day.

Literature Review:

Goals of the Literature Review:

This paper is focused solely on the management of space debris in LEO. Other space policy issues like ownership of the moon or asteroids are too broad for the scope of this analysis. There is no doubt that space debris in LEO is a problem. Space debris is primarily small, difficult or impossible to track, and highly destructive at great velocities. Yet exactly how large the scale of the problem is remains a point of contention. Is space debris simply an issue that might be worth investigating in the future? Or is it already near a crisis point that requires more drastic policy measures? This review looks to gauge the extent of the space debris problem and probe into the feasibility and effectiveness of two general solutions. The first is industry standards and other passive controls. The second would be a more aggressive international collaboration similar to the regulations placed on GEO or even active removal.

As seen in the comparative matrix (Table 1), sources are identified by author and background and rated on how urgent they perceived the problem of space debris. Each paper is evaluated by how dangerous they believe the risk of space debris is, whether or not they believe the problem of space debris is self-propagating in nature, and whether an international agreement on the issue is possible. Then they are assessed over whether or not active removal missions are necessary to control space debris and if the 25-year rule, a passive measure, is adequate to solving the problem of space debris. X’s indicate a general response of “yes”, blank meaning “no” and a slash through them meaning the issue is specifically not addressed. The latter is usually the case with academic papers, who want to study the issue of space debris without making claims as to the best solution.

Source	Year	Type of Source	Risk Level	Self-Propagation?	International Solution Possible?	Active Removal Advocated?	25 Year Rule?
Adilov	2015	Government	Urgent	x		x	x
Ansdell	2016	Policy Journalist	High	x		x	x
Carroll	2013	Aerospace Engineer	Urgent	x		x	x
Castronuovo	2011	Aerospace Engineer	High	x	x	x	x
Chen	2011	Policy Journalist	Low	x			x
Crowther	2002	Policy Journalist	Low		x		
Durrieu	2013	Policy Journalist	High	x	x		x
Grego	2017	Government	Urgent	x			
Hildreth	2014	Government	High	x		x	x
Johnson	2007	Aerospace Engineers	Urgent	x	x	x	x
Krisko	2007	Aerospace Engineers	High	x			
Levin	2012	Aerospace Engineers	High	x		x	x
Liou	2010	Astronomer	Urgent	x	x	x	x
McCormick	2013	Policy Journalist	High	x	x		x
Mirmina	2005	Legal Journalist	Low	x			x
Percy	2014	Government	High				x
Walker	2004	Academic	Low	x	x		x
Weeden	2011	Policy Journalist	High				x
Wislon	2003	Academic	Low	x			

Table 1: Comparative Matrix of Sources

Scope of the Problem:

The chief problem with space debris is that it travels at such high velocities and so much of it is small and untraceable. The Space Surveillance Network (SSN) tracked around 8500 objects in orbit in 2003, but could not see any objects smaller than 10 cm in diameter (Wilson, 2003). Even as tracking technology and imaging software improves, tracking 10 cm objects is still tough. Debris between 1 cm and 10 cm cannot be tracked, but can still destroy a satellite (Adilov, 2015). This is because orbital velocities of several kilometers per second mean that even granular space debris can cause massive damage to space vehicles, satellites, and astronauts in LEO. There is no economical way to track and remove objects this small, so the only way they can be cleared is for their orbits to passively decay into the atmosphere over time. If the objects are at the edge of LEO, this can happen in a few days. But the greatest density of objects in LEO is estimated to be around 880 km above the surface and decay from this point can take decades or even centuries (Wilson, 2003). Even as developing nations and private companies plan massive new constellations of satellites for the next decade, debris from the 1970s and 1980s can still pose a major hazard to new launches. Of the 19 sources addressed in this review, all but 5 agree that orbital debris is a serious concern that requires some form of intervention.

All of the source assessed by this review were examined by the scale of the problem they argued debris in orbit could pose. Based off the language of the report, an indicator word was assigned which can be seen in the comparative matrix (Table 1). Nearly all sources stated that orbital debris was a problem, but the nature of the problem could change from source to source. The most alarmist statistic was an estimate that the chance of a catastrophic collision in LEO is about 6% annually (Carroll, 2013). If true, this would be devastating to national security, Earth observation and weather, and communications technology. Large collisions have the capacity to generate large clouds of debris which can badly damage other satellites nearby. Whether or not there is a critical mass of debris in orbit now to self-propagate the creation of new debris without additional launches is examined in the next section.

Self-Propagation of Debris:

A point of contention among experts is to what degree this problem will self-propagate. Similar to a nuclear chain reaction, each collision among satellites or space debris will generate far greater numbers of smaller pieces of debris which can potentially cause more collisions. If there is a sufficiently high density of satellites in LEO, debris created by collision will readily find new targets and the amount of total objects will increase exponentially. There is no question that collisions cause more debris, but the question is whether or not there is sufficient density of objects in LEO to rapidly propagate more debris. Sources that believe the problem of self-propagating debris would grow exponentially would answer “yes” to the column of the comparative matrix. Sources that answer “no” recognize that collision between debris can cause more debris, but they do not take this into account when modelling the debris in orbit. Laura Grego mentions that half of the eight known collisions of space objects have happened since 2005 and implies that the magnitude of the problem is only growing (Grego, 2011). The International Academy of Astronautics estimated in 2006 that 94% of all objects tracked by the United States and Russian SSN were inactive pieces of debris, most of which is small fragments that broke off during missions or the resulting from collisions between debris pieces (Dansey, 2006).

However the self-propagation of space debris is not mentioned by all studies on the subject. To clarify, not all sources agree that there is enough proliferation of debris to drastically change the scope of the problem. All sources recognize the basic physics that collisions with debris will produce more debris. Crowther reports that impacts from space debris, natural and manmade, are common due to the visible pitting and corroding on satellites (Crowther, 2002). But Crowther goes on to mention that most collisions are from very small particles that vaporize on impact. Collisions with objects greater than 1 cm, which can cause serious structural damage and are impossible to shield against, are far less common, and merely planning smarter flight paths to avoid areas of high debris density is mitigation enough. Percy also agrees that the debris environment has more to do with high traffic orbits and makes no mention of the self-propagation of debris (Percy, 2014). Again, there is the argument that without sufficient density of objects, which is what managing orbits would do, there is not enough mass in orbit to proliferate enough chain reactions of debris collisions in order to dramatically change the scope of the problem.

Unsurprisingly, studies that account for propagation of debris as a significant factor in the question of LEO management will argue that space debris is a very urgent issue. All but 2 sources maintain that self-propagation of debris is a major issue in considering the problem of orbital debris. The chain reaction of debris in sufficient density will combine with the uptake in the number of orbiting objects in recent years to easily overrun the rate at which those orbiting objects decay. The result would turn LEO into a ring of debris that makes space unusable for anyone due to the destructive nature of hypervelocity impacts. If self-propagation is a significant factor in the model, the situation of debris in LEO becomes more urgent. It might even suggest more aggressive plans like active removal of debris be put into place.

Feasibility of an International Solution:

Space falls into the unfortunate category of being both increasingly vital as well as increasing unclear about who has access to use it for what purpose. In an idealized world, the United Nations would hash out a binding series of policies that kept space open for all and limited the damaging effects of space debris. In reality, the problem of space debris is more like the problem of climate change and pollution on Earth. Both problems involve mankind filling areas with waste and it would be nicer for everyone if there were less waste. However, in both cases either slowing the rate of waste creation or cleaning up what is already there is not a popular course of action for any of the participants. Cleaning space up and managing it better would benefit all spacefaring nations, yet following policies that achieve this may not. And under the notion that space is already “the common heritage of mankind”, any nation could claim its right to access over its need to participate in international policy.

For example, one policy that can limit the spread and effect of space debris is to carry less fuel on board spacecraft and satellites in orbit. Hypervelocity impacts of anything greater than about 1 cm in diameter cannot be adequately shielded, but the damage can be minimized if there are not very full fuel tanks to aim at (Dansey, 2006). Carrying less fuel is already a cornerstone of industrial standards mainly because it is attractive economically as well as being good for debris management by mitigating the possibility of large explosions. The less weight a spacecraft carries, the less energy is needed to get it to orbit and the cheaper the mission becomes.

International agreements about other policies to mitigate debris and overcrowding, such as those used by the International Telecommunications Union in GEO, are much trickier to implement unilaterally. This is mostly due to the tragedy of the commons, an economic theory that in the case of a shared resource, individuals will act contrary to the collective good and spoil the resource in order to make gains themselves. Clean space would be a benefit to all spacefaring organizations, and yet the cleaning of space can be potentially very costly. It would not be surprising if countries did not want to undertake burden of clearing objects from orbit when they can only reap the same benefits as everyone else, including countries that undertake no mitigation or removal efforts whatsoever. The better course in this case would be to do nothing about debris control while hoping that other nations and private companies would.

However, this dilemma does not mean that international cooperation on the issue of space debris is impossible. Crowther (2002) indicates that there is already widespread interest in cooperation among spacefaring nations through the creation of the Inter-Agency Debris Coordination Group. This group has already received endorsement from the United Nations Committee for the Peaceful Uses of Outer Space and had outlined preliminary mitigation efforts in London in 2002. The severity and awareness of space debris has only grown since then, so it's safe to assume that a similar spirit of cooperation exists today. The fact that the number of space-capable agencies, national and private, is still relatively small and that the field is made of technical experts means that cooperation for mutual benefit is not so far-fetched a goal. The highly focused and technical nature of the topic means that space debris is an issue that, for the moment, seems literally and figuratively above political polarization. Given the technical nature of the problem, the possibility of a successful clean space initiative among spacefaring nations is fairly high (McCormick, 2013). The remaining question then is not if international regulation of space is passed, but rather what types of precedents it sets. Passing policies now would fall to the 20 or so most wealthy nations of the world but would technically apply unilaterally, even to nations and corporations that have plans to move into space but are not yet spacefaring.

Not all papers remain so optimistic that an international agreement of any kind is possible. Some argue that mitigation efforts, such as increased communication and transparency about satellite plans are important but not enough on their own to solve the issue of orbital debris in LEO (Hildreth, 2014). Through the use of tools like the SSN, countries can share information about object locations and speeds and help nations guide their active satellites out of the way of debris with advanced warnings. While these measures are important to fostering a sense of trust in the international community, they are purely voluntary. Another crucial factor is that there is currently no legal distinction between debris and active satellites (Weeden, 2011). Like all other machines, satellites have life expectancies and also the possibility of outliving them, making them active but labelled as defunct. If an active removal program is initiated, the gray area between functional and defunct satellites could pose a serious obstacle. This legal no man's land gets even more complicated as competition for prime orbit spots is likely to intensify. For instance, a communications satellite over the Sahara Desert is essentially worthless while one over Europe and North America is extremely valuable. This begs the question if nations are allowed to have written off, but possibly still somewhat functional satellites in prime orbital configurations. Given the vague legal language of the issue and the idea that any international policy is based solely on goodwill, some would argue that reaching an international agreement that has a serious impact on cleaning LEO is highly unlikely.

A quasi-consensus can be drawn regarding space debris in international policy arenas: that space debris is a problem that should be addressed by the world's leading spacefaring nations. Access to space will only improve and the number of stakeholders involved will only increase in the future. The sources in this review that offer opinions on the feasibility of international cooperation in managing orbital debris are exactly split at 6 to a side. One side believes the issue is already too complicated and competition among stakeholders is already to great to render an easy solution to the problem. Another side is more optimistic, saying that the scope of the problem is limited to just a few stakeholders and is highly technical in nature. They also point out that some international efforts are already making headway. Regardless, a Cold War arms treaty is insufficient to govern outer space and new agreements will have to be reached, which may even remove the "common heritage" label for space altogether.

Active Removal:

Active removal of debris is defined as the use of special space missions to pull objects out of orbit and into the atmosphere where they can be burned up. This strategy focuses on large pieces of debris as smaller pieces cannot be tracked or efficiently removed. By eliminating large objects in crowded orbits, active removal remedies the possibility that catastrophic collisions might result in self-propagation of debris clouds and make LEO all but unusable to future generations. Unsurprisingly, the more urgent the problem of orbital debris is made out to be, the more attractive active removal becomes as opposed to simply passively allowing objects to deorbit on their own.

Active removal of space debris can undoubtedly lessen the future impact of self-propagation of debris in the future, even though it is limited to large orbital debris pieces as smaller pieces are impossible to track. Yet without new developing technology, it is possible that active removal will prove too expensive to be worth the benefit of cleaner space. A new method of electrical propulsion may make active removal more cost effective, eliminating 99% of the potential for debris to self-propagate in LEO (Levin, 2012). The economics of such a solution are highly attractive as a significant probability for disastrous collisions is averted for all time based off of a relatively small expense in the present. Another proposal states that removing just 35 large objects from LEO over the next 7 years using robotic spacecraft is technically feasible (Castronuovo, 2011). Assuming the scale of the problem of orbital debris is great enough, active removal is justifiable from a purely economic standpoint and certainly well within human limits technologically. Another interesting proposal uses expanding foam to increase the surface area of a satellite after its useful life is concluded in order to remove satellites without added fuel (Andrenucci, 2011). While not within the definition of active removal in terms of additional missions to remove debris, the study shows that there are creative ways of clearing orbits that can be quite cost effective. As the cost of orbital missions continues to decrease and the utility of space increases, active removal will likely become even more attractive in the years to come.

But even with technology to make active removal into a more plausible solution, there are policy and legal challenges that complicate the issue. There is no international consensus on which pieces of debris should be targeted for removal and no clear notion of who legally has the right to remove debris (Weeden, 2011). In fact, since there is no overarching international body that can either claim or delegate the right to remove debris, individual nations may take to active removal as a means to secure access to space for themselves. One source argues that the United States should aggressively conduct its own active removal in the hopes that it will serve as an example to other nations to manage their own debris (Ansdell, 2016). Since only removing a handful of large objects per year could dramatically lower the chance of collisions, this position states that it would be better to go ahead with active removal and deal with any legal or policy ramifications after the fact than to not do it at all.

The 25 Year Rule and Other Best Practices:

Assuming all spacefaring entities worldwide could agree on general practices and policies to follow to keep LEO clean and accessible, what kind of policies should be pursued? One of the favorite suggestions is the so-called “25 year rule” which states that no country or corporation can intentionally leave a piece of debris, be it a rocket booster or a satellite, in orbit for longer than 25 years. Space vehicles must usually expend at least a little fuel in order to stay in LEO. The idea is that when 25 years is up, regardless if the satellite is still functional, it should use its last bit of fuel to send it on an orbit that rapidly decays into the upper atmosphere. Of course this limits its application to future launches only and has no bearing on debris already in orbit.

Nearly all of the policy proposals studied in this literature review mention the 25 year rule and advocate its use as a voluntary measure that can curb the growing number of space debris in LEO. Some argue that voluntary measures like these are the only ones needed. Mirmina points out that the IADC group’s voluntary standards on post-mission disposal and the design of launch vehicles and satellites to minimize debris caused during normal operation are similar to the Missile Technology Control Regime, a series of voluntary standards starting in 1987 to keep technical information about ballistic missiles and warheads out of unfriendly hands (Mirmina, 2004). The Missile Technology Control Regime has no penalties enforced, and yet has been adopted by the United States, Japan, Russia, and other major world powers. The standard is updated to meet current needs and most member nations impose penalties internally to ensure compliance. Thus, a unilateral agreement to a policy like the 25 year rule could have an equally profound effect at mitigating space debris.

Other sources would argue that the 25 year rule is a good start, but that the debris problem in LEO requires more aggressive action, such as active removal. Hildreth makes a point that Congress needs to look into the resources NASA would need to lead an effective active removal effort (Hildreth, 2014). This paper argues that orbital debris is primarily a national security concern; that the debris problem is already advanced enough in LEO that voluntary measures alone are inadequate to resolve the issue. Policy strategists at the Aerospace Corporation, a government research center closely linked to the Air Force space programs and National Security space, even suggest that licensing of orbital spots might be necessary to limit the number of satellites that can be put up (Gangestad, 2017). This becomes a tricky solution because it gets back to the whole paradox of “common heritage”. Even a third party with the best of intentions is liable to severely restrict access to space, perhaps along biased lines. Active removal of five objects per year might stabilize LEO within 200 years (Liou, 2010). This would mean a high cost and an accompanying persistent mitigation effort for the next two centuries just to stabilize the orbit. Given the legal gray area, deciding who has the right to remove what can also be tricky.

Technical studies are less forward about suggestions such as active removal or licensing and are more inclined to fall back onto the 25 year rule and other practices that are already quite standard in the industry. The 25 year rule was recognized as the most cost effective way of eventually clearing LEO (Walker, 2004). The tradeoff to this cost effectiveness is the timescale of the solution. If the 25 year rule does not adequately control the issue of space debris, then self-propagation and more frequent collisions are liable to dramatically increase the scale of the problem

The 25 year rule is not the only standard that can be pursued. As mentioned previously, better satellite and launch vehicle design can help prevent debris from breaking away during vehicle operation. It is also quite common to keep fuel levels onboard spacecraft at the absolute minimum while in orbit. Writing out a policy for minimal fuel payloads is unnecessary, however. Extra fuel means extra weight. And after all, the price to orbit for most rockets today is in the area of $15,000 to $20,000 per kg. This makes carrying unnecessary shielding or fuel highly undesirable due to pure economics. Eliminating extra fuel reduces the risk of explosions as well as the cost of a mission. Up to 2005, there have been over 180 in orbit explosions that have created nearly 40% of all space debris (Dansey, 2006). The quantity of debris in orbit is only increasing so mitigating future explosions will be essential to controlling the problem.

Of the 12 sources that offer policy recommendations, 10 agree that passive measures like the 25 year rule are good policies to pursue in managing orbital debris. Practices like the 25 year rule, sturdier satellite design, and carrying less fuel seem to be common sense approaches that all sources agree on. The issues is if passive measures alone are enough to properly manage orbital debris. Of the 12 sources offering opinions, 4 say that passive measures alone are not enough and state that active removal missions are needed to clear debris out of orbit. The remaining sources argue that the cost of sending specialized space vehicles purely to remove debris is not justified given the scale of the problem itself.

Conclusion:

There is already a unanimous consensus among the sources reviewed that orbital debris in LEO is a problem. Nobody disputes that hypervelocity impacts are dangerous even with particles down to 1 cm diameter and it is nearly impossible to track particles less than 10 cm in size. As has happened with policies and regulations concerning clean air and water, the notion of clean space is held as an ideal. It will preserve the economic value of space for future generations and protect the security interests of spacefaring nations, not to mention the treasure trove of climate and weather data that comes from space. Also, it is generally believed that industrial best practices like better satellite design and carrying less fuel onboard satellites are mitigation strategies enough.

The 25 year rule in particular seems to be popular across the board as a strategy for managing debris. Because most space debris is smaller, sending missions to actively remove it becomes incredibly difficult and costly. Better orbit planning through the 25 year rule uses natural orbital decay into the atmosphere as a way to remove defunct satellites and boosters from orbit. This makes the 25 year far more feasible than active removal.

The disagreement over debris mitigation policy comes in two primary forms. Some think that further international policies other than purely voluntary standards are unfeasible and unenforceable in space, with only 7 of 19 sources arguing to the contrary. Although the spacefaring community is a small number of agencies and technically sophisticated companies, they would argue that unilateral rules are not passable because it is against the self-interest of the nations and corporations involved. Others would say these characteristics make the space community much more amenable to cooperation than has been seen so far in the international discussions and regulations on climate change.

The second form of disagreement is over whether passive measures like the 25 year rule are adequate at all. More direct measures of dealing with debris, such as active removal, are then made necessary if passive measures are inadequate. Eight of the sources argue that active removal is necessary while two declined to take a stance on the issue. Active removal is certainly technically feasible, but there are several legal and policy questions that must be answered before. The most important of these would be the establishment of a consistent legal definition for what debris is and the assignment of responsibility for debris, including its removal from orbit. Regardless of whether active removal missions are aggressively pursued in the near future, the creation of an international consensus on these questions should be a near term priority.

To conclude, orbital debris is a current issue and has the potential to be a serious problem in the coming decades and centuries if business as usual is conducted. Fortunately, steps are being taken now which can mitigate this disastrous scenario. The space community is still relatively small and better rocket and satellite design is helping to avoid the accidental creation of debris. Studies over the feasibility of pulling large objects from orbit have already been done and they show a large amount of promise for managing the future creation of debris very effectively. Although current international policies managing debris do not yet exist, the discussion over how space will be managed is already well underway. If sound debris policies can come out of these discussions, the utility of LEO can be preserved for future generations.

Statement of Purpose:

Orbital debris is a clear and distinct threat to the future accessibility of space. As the current Outer Space Treaty is inadequate, new policies and initiatives will need to be undertaken to ensure the future utility of space for all nations. There are several projections for what LEO might look like under various scenarios, from business as usual to aggressive active removal of debris, as well as several creative measures to mitigate the creation of debris and move defunct spacecraft and satellites into atmosphere. Yet before any of these measures are to be implemented, an understanding of the value of clean space should be established. Any potential solutions would then have their benefits in terms of clean space measured against their costs to determine whether or not the interventions proposed are appropriate.

Finding a cost for clean space in LEO is the purpose of this paper. The policy proposal to be examined requires all spacecraft that would normally launch to LEO to instead be launched into MEO. At the end of the useful life of the spacecraft, it would be maneuvered into LEO where it could slowly decay into the upper atmosphere. In essence, this proposal would seek to do nothing to control debris in LEO and would protect useful satellites by moving to an area with less debris. This proposal is a passive measure, and therefore any active removal efforts should cost less than simply bypassing LEO for an extended period of time.

Methods:

In order to calculate the fuel cost of launching above LEO, the number of launches intended for LEO in the near future have to be predicted. This prediction would be done through a regression of previous launch data. From 2004 through 2017, this trend was fairly linear and so a linear regression would be extrapolated beyond 2017 to estimate the number of launches to LEO in the future. Upper and lower limits would be established by the upper and lower bounds of the 95% confidence interval of the slope in the regression to estimate a range of possible future values.

By using approximated drag coefficients and estimates for atmospheric density, it is possible to estimate how long something will remain in orbit until frictional forces pull it back into the atmosphere. This will be used to determine how much of the debris currently in LEO will fall out of orbit during the time when LEO would be bypassed by functional satellites and rockets. While these calculations are nowhere near as precise as the regression estimate range, they still provide a good benchmark for how much debris might be removed given a certain amount of time to decay into the atmosphere.

A Hohmann transfer is used to estimate the additional fuel cost of each launch as it is the most energy efficient way to move between two nearly circular orbits. Most launches are quoted to 800 km, which is a standard altitude for LEO satellites. Using a Hohmann transfer to move to between 2000 and 4000 km, the lower range of MEO, it is possible to find a change in velocity needed to make this change in altitude. Assuming a mass for the rocket's second stage, the primary engine for making this transfer, as well as a fuel to be used, the mass of fuel can be calculated and from there the cost.

Finally, by pulling together the estimates for number of launches from the regression and the additional cost per launch, the total cost can be determined between now and 2050. After 2050, it is not practical to extrapolate the linear regression nor is there a great return on investment with the amount of debris that would have cleared out of LEO.

Calculations:

Predicting the Number of Launches:

Once the time scale of the problem is established, the cost of launching to higher altitude orbits can be estimated. In order to do this, the total number of intended launches to LEO needs to be established. Figure 2 shows data about launches to LEO from the Space Launch Log Report (Kyle, 2018), a record of launches by nationality, vehicle type, payload, and orbital destinations over the last 20 years. The general trend shows that recently there has been an increasing number of launches to LEO despite a decreasing trend in the early 2000s. Looking closely, it seems that the trend in launches to LEO since 2004 has been a positive, linear trend. This trend makes sense as there are an increasing number of private companies and developing countries that have increased their spacefaring capabilities dramatically in the last decade. As space infrastructure becomes more valuable, even established spacefaring nations have plans to augment their presence in space. Assessing the years from 2004-2017 and performing a regression analysis yielded the following results, as seen below in Figure 3 and Table 2:

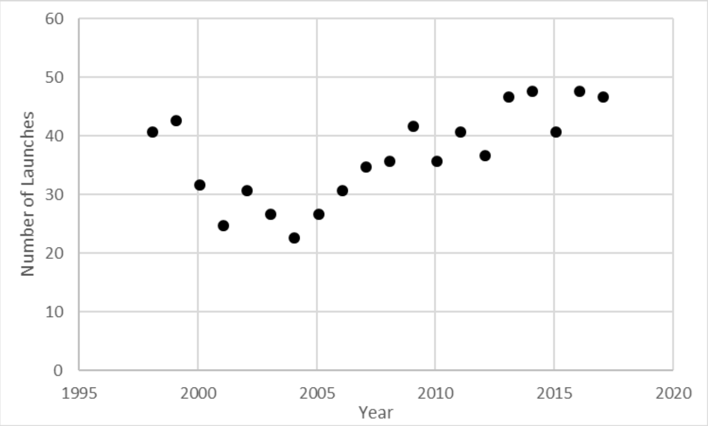


Figure 2: Annual launches to LEO

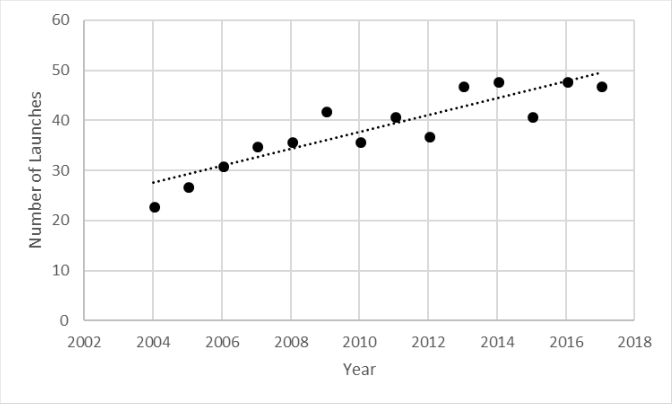
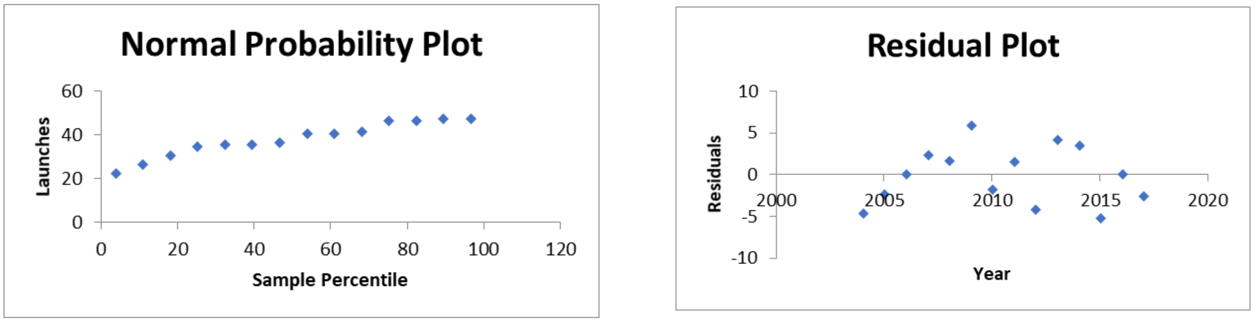


Figure 3: Regression analysis of annual launches to LEO

Parameter	Value
Slope	1.69
Intercept	-3359.5
Slope Confidence Interval, 95% level	(1.17, 2.21)
R-squared	0.806
Adjusted R-squared	0.791

Table 2: Regression statistics for annual launches to LEO



Figures 4 and 5: Normal probability plot and residual plot of regression analysis

The slope of the regression output indicates that there are an additional 1.69 launches to LEO every year. The confidence interval of the slope excludes 0, meaning that the relationship of number of launches to LEO over time has statistical significance. The R-squared and adjusted R-squared values are higher than expected, with about 80% of the variation in launches being explained over time. The residual and normalized residual plots do not show any patterns to suggest that the residuals are not normal and randomly distributed. Therefore, linear regression is a valid method for approximating future launches to LEO.

In order to create a range of expected launches, the high and low slope values from the 95% confidence interval will be used. The last point approximated in the regression line is for 2017, with the regression estimating 49.5 launches compared with the actual value of 47. Using point-slope from, the upper and lower bound of the predicted range follow as such to give a range of possible launch values that grows with distance from the present.

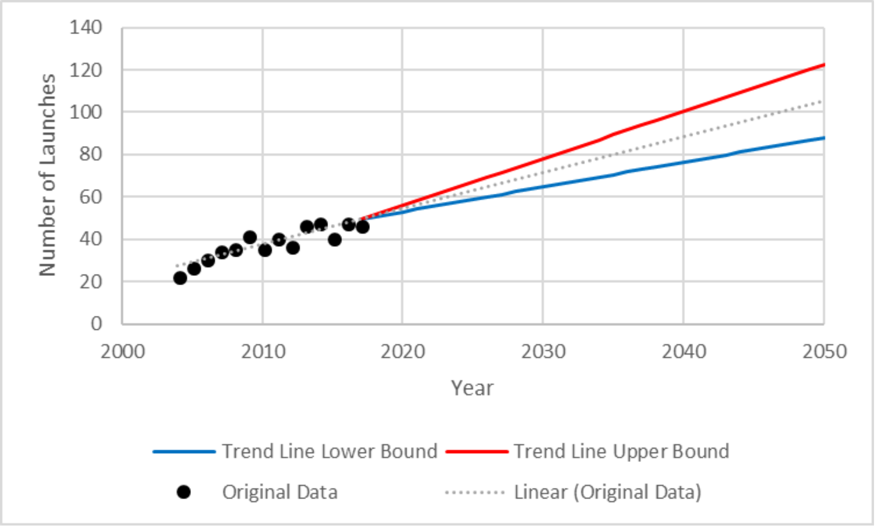


Figure 6: Regression analysis with projection range into

$$Lower\ launch\ estimate = 1.17(year - 2017) + 49.5 \quad (1)$$

$$Upper\ launch\ estimate = 2.21(year - 2017) + 49.5 \quad (2)$$

Determining a Time Scale:

Even though the regression range of possible launches grows by year, interpolating future trends based only off data from 2004-2017 might prove inaccurate. Establishing a time scale for how long it will take to clear LEO is then necessary to judge how far into the future the launch regression needs to go. All objects greater than 10 cm in diameter are currently tracked by both observatories on the ground and some satellites in GEO. The log of this data is kept by the Joint Space Operation Center in the United States Air Force (Space-Track, 2018). This data keeps track of everything from debris launch date, re-entry date (if applicable), orbital period, apogee, and perigee. Currently, there are 15,406 objects in LEO according to this database.

Using this data, it is possible to approximate when these objects might fall out of orbit and burn up in the upper atmosphere. Other than any onboard propulsion, the only significant force acting on a piece of orbital debris is atmospheric drag. Although the atmosphere in LEO is extremely thin, the high speed of satellites make this tiny drag force significant over time in causing orbits to decay. The magnitude of this force can be used to approximate how long it will take for a satellite to fall out of orbit.

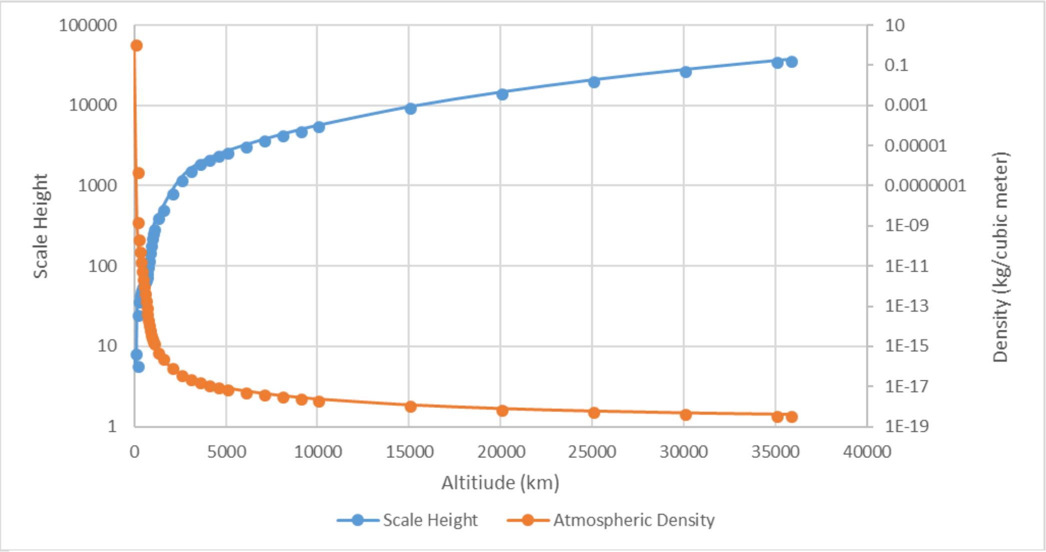


Figure 7: Atmospheric density and scale height at various altitudes (Braeunig, 2013).

Given a satellite's apogee and perigee, the orbit of a satellite can be approximated as a circular orbit with a new effective height using equations 3 and 4 (Australia, 1999), where q is the perigee or lowest altitude of the orbit in km, a is the apogee or highest altitude, Re is the radius of the Earth, and e is the eccentricity of the orbit.

$$h_e = q + 900(e)^{0.6} \quad (3)$$

$$e = \frac{(a+R_e)-(q+R_e)}{(a+R_e)+(q+R_e)} \quad (4)$$

An average velocity was then be applied to all 15,406 objects currently in LEO knowing only the perigee and apogee of each orbit. This is only an average velocity as most orbits are highly eccentric. The closer and object is to the Earth, the faster it will travel. However, simplifying each orbit as circular with an effective height allows the computation to be made much more easily while still retaining some degree of accuracy, which is why the Australian Space Weather Agency chooses to use this approximation. After finding the velocity, the change in apogee per revolution on an object is found using equation 5 (Braeunig, 2013). All velocities must be input in meters per second to keep with the consistent SI units. A is taken to be the cross sectional area, Cd is the drag coefficient, v is the velocity, ρ is the density of the atmosphere, and m is the mass of the satellite. For the sake of simplicity, all objects are assumed to be 100 kg in mass and having a drag coefficient of 2.2 and a cross sectional area of 1 square meter. The atmospheric density is inferred by using the graph in Figure 7. The sign of equation 6 is negative because as the drag force on an object detracts from its momentum.

$$\Delta a_{rev} = \frac{-2\pi C_d A \rho a^2}{m} \qquad (5)$$

Finally, by using the change in apogee per revolution, the lifetime of the satellite can be approximated assuming that no external forces other than atmospheric drag. H is given as the scale height of the object and is graphed alongside atmospheric density in Figure a.

$$Lifetime \approx \frac{-H}{\Delta a_{rev}} \quad (6)$$

As with all of these calculations, this is only a rough estimate. Variability in object masses, cross sectional areas, and variable atmospheric density as the orbit decays all play a role in when an object deorbits. The altitude of deorbiting is assumed to be 188 km above the Earth, when atmospheric density is great enough that any satellite at this altitude will burn up in a matter of hours. The period of orbit at this altitude is 88.1 minutes. Assuming a constant drag force, the average period of a decaying object will be the arithmetic average of its initial period and its final period. Because atmospheric drag is not constant throughout the decay, this assumption is not valid for precise calculation but suffices for an estimate.

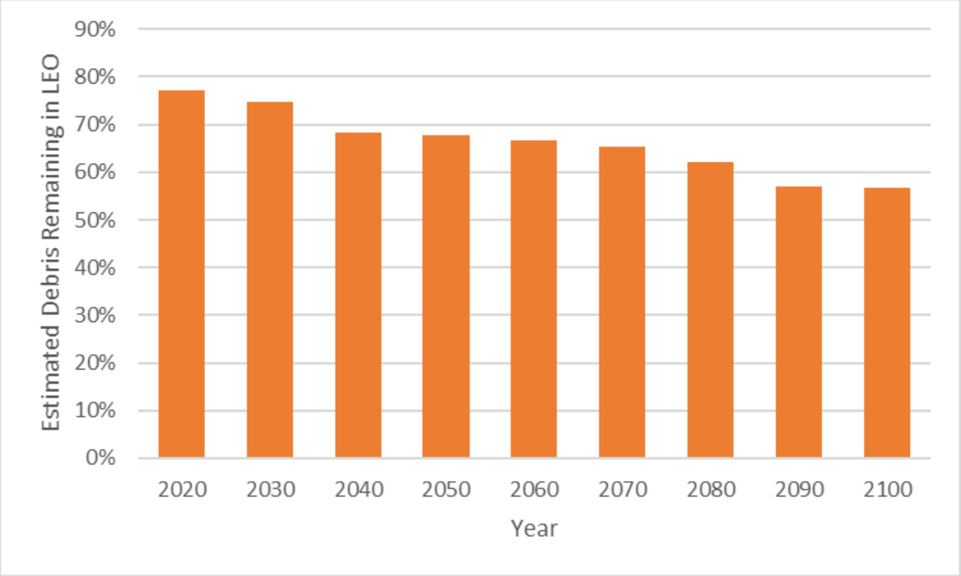


Figure 8: Estimated percentage of objects remaining in LEO over time

Once the lifetime in revolutions is multiplied by the average period per revolution, the lifetime of an object is determined. Going back to the original data, by adding the lifetime to the original launch date of the object, a re-entry date is calculated. Figure 8 shows what percentage of objects currently in LEO are expected to remain in LEO over the given time span. By 2050, about a third of the objects in LEO are expected to fall out of orbit. But by 2100, over half of the objects currently in LEO will remain. If the object is more than 500 km above the Earth, its lifetime is on the order of decades or even centuries. This is a major contributing factor to the problem of space debris, where an object that is launched today may not re-enter the atmosphere for another quarter millennium or more.

This model of predicting when objects will deorbit has some inconsistencies. According to the model, some pieces of debris that are still in orbit should have deorbited in the 1960s and 1970s. And other pieces of debris have a lifetime of several centuries when they normally would have lifetimes of a few decades at their particular altitude. These inconsistencies arise from the assumptions made in the model and the fact that the model is a first pass approximation. Having a variable atmospheric density and inserting accurate cross sectional areas and drag coefficients would remedy these errors. However accurate data about debris cross sectional areas does not exist and having a variable atmospheric density above 500 km would have required extensive computer modelling that is not used in this report.

For the purposes of this analysis, 2050 is a reasonable end date. Extrapolating the linear regression model beyond this is not likely to be accurate and there is a diminishing return of allowing orbital debris to re-enter the atmosphere. Figure 8 shows that launching to higher orbits will not clear out LEO anytime soon. However, by launching operational satellites to MEO and then moving them into LEO as a “graveyard orbit” will limit the likelihood of a collision during the operational lifetime of the satellite.

Fuel Cost of Launching to MEO:

A standard launch altitude for LEO is 800 km and launch prices for most vehicles in service are quoted to this value. Of the rockets most commonly used in 2017, all of them have the capability of launching to higher orbits although some seem to specialize in launches to LEO. The Antares 230 from Orbital ATK and the Vega from ArianeSpace logged no launches above LEO in the last 10 years. The Chinese Chang Zheng 5 and the Russian R7 series are heavily used from launches to LEO although they have capabilities to launch higher. Table 3 lists specifications for the most common rockets used and their cost per kilogram of payload for launching to an altitude of 800 km for LEO. The data for number of launches is again from the Space Launch Report (Kyle, 2018).

Vehicle	Manufacturer	Country	Debut Year	Total Launches to LEO since 2008	Total Launches >LEO since 2008	Total Failures since 2008	Total Mass at Ground (tonnes)	Payload Size to LEO (kg)	Cost per Launch ($MM)	Cost/kg
Falcon-9	Space-X	United States	2010	31	22	2	505.846	13150	62	$ 4,714.83
Falcon Heavy	Space-X	United States	2018	0	1	0	1462.836	53000	90	$ 1,698.11
Soyuz-2-1v (R7)	TsSKB Progress	Russia	2013	63	22	4	157	2850	48	$ 16,842.11
Atlas-V	United Launch Alliance	United States	2002	18	44	0	590	18850	109	$ 5,782.49
Chang Zheng 5	China Academy of Launch Vehicle Technology	China	2008	97	61	6	867	25000	70	$ 2,800.00
Ariane-5	ArianeSpace	ESA	2003	7	58	1	780	20000	60	$ 3,000.00
H-2A	Mitsubishi Heavy Industries	Japan	2001	14	11	0	500	14000	90	$ 6,428.57
Proton (UR-500)	Khrunichev	Russia	1965	0	85	9	705	22800	65	$ 2,850.88
Vega	ArianeSpace	ESA	2012	10	0	0	137	1500	37	$ 24,666.67
PSLV	Indian Space Research Organization	India	1993	20	12	1	320	1750	26	$ 14,857.14
Antares 230	Orbital ATK	United States	2013	7	0	1	296	8000	82.5	$ 10,312.50

Table 3: Most common launch vehicles to LEO. Launch data from (Kyle, 2018). Rocket data from (Falcon 9, 2013), (Falcon Heavy, 2018), (Capabilities and Services, 2018), (Soyuz-2-1v, 2018), (Atlas-V, 2018), (Chang Zheng 5, 2018), (De Selding, 2013), (Ariane 5, 2018), (HII-A, 2017), (ILS Proton Breeze, 2013), (Vega, 2018), (Polar Satellite Launch Vehicle, 2017), and (Antares, 2018).

A Hohmann transfer orbit is used to simulate the additional fuel used to launch to orbits that are higher than the 800 km altitude quoted in the table. The Hohmann transfer is the most energy efficient maneuver to move between two circular orbits as shown in the diagram, involving an elliptical orbit to connect the two. Fuel is consumed at two points, one to move into the elliptical transfer and one to move out of it into the final orbit. For this particular policy proposal, fuel will be needed at the beginning and end of the life of a satellite. In the beginning, a transfer from 800 km to at least 2000 km is needed to cross into MEO. At the end of life, the transfer will be from at least 2000 km to 300 km so that it decays into the atmosphere within a couple of years.

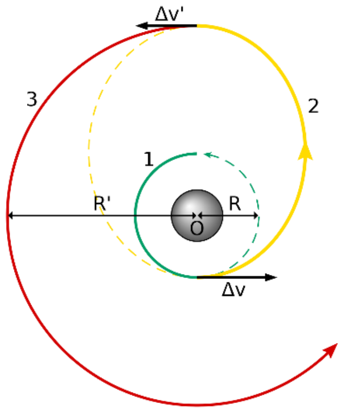


Figure 9: A Hohmann transfer

The first stage of a Hohmann transfer is the move to the elliptical orbit (Curtis, 2014). Equation 7 is used to find the angular momentum (h) of the first orbit, where the eccentricity is assumed to be 0 for a circular orbit and R is the radius of the Earth plus the altitude of the orbit. The standard gravitational parameter (μ) of Earth is equal to 398,600 km3/s2.

$$R = \frac{h^2}{\mu}\frac{1}{1+e\cos(0)} \qquad (7)$$

After finding the angular momentum, equation 8 is used to find the velocity.

$$v = \frac{h}{R} \qquad (8)$$

Equations 7 and 8 are then used again with the old radius being the perigee of the transfer ellipse and the new radius being the apogee of the ellipse, if the spacecraft is maneuvering to a higher orbit and the reverse if it is moving to a lower one. The final velocity is found using equation 9. The total change in velocity needed to move to the higher orbit is the result of the two impulses to move into and out of the transfer elliptical orbit as shown in equation 10.

$$v_3 = \sqrt{\frac{\mu}{R\prime}} \qquad (9)$$

$$\Delta v = \left|v_3 - v_{2,apogee}\right| - \left|v_{2,perigee} - v_1\right| \qquad (10)$$

Once the change in velocity of a transfer is known, the mass of fuel needed to complete the transfer can be found. The table below lists the impulses of some common fuels, although liquid hydrogen and liquid oxygen is the most common and will be assumed for this study.

Propellant	**Isp (seconds)**
Cold gas	50
Monopropellant hydrazine	230
Solid propellant	290
Nitric acid/monomethylhydrazine	310
Liquid oxygen/Liquid Hydrogen	455

Table 4: From *Orbital Mechanics for Engineering Students*, page 257

Equation 11 calculates the mass of fuel burned from the impulse values of the fuel and the required change in velocity. The mass of the vehicle, m, is the mass of the second stage of the rocket in kg. A single stage launch to orbit has not yet been obtained, so the transfer from LEO to MEO must make use of a second stage. The second stage mass is that of a Falcon-9 rocket, one of the more common launch vehicles currently in use (Falcon 9, 2013).

$$\frac{\Delta m}{m} = 1 - e^{\frac{-\Delta v}{I_{sp} \cdot g_0}} \quad (11)$$

After accounting for the Hohmann transfer into and out of MEO over the useful life of a satellite, the change in velocities needed and the mass of liquid hydrogen and oxygen needed to obtain them are shown in the table below. A range of altitudes is displayed because the primary attraction of MEO is extra space for operational satellites. Launching satellites to only a narrow band within MEO contradicts this goal.

Altitude (km)	Delta V (km/s)	Extra Fuel per Launch (kg)
2000	2.91	19,711
2500	3.76	25,022
3000	4.56	29,291
3500	5.31	32,780
4000	6.03	35,671

Table 5: Masses of liquid hydrogen and oxygen required to reach new orbits in MEO

Results, Discussion, and Recommendation:

Cost of Launching to MEO:

The total cost of launching satellites intended for LEO to MEO is primarily a matter of extra fuel costs to get to MEO and then back to LEO at the end of a satellite's operational lifetime. Most launch vehicles in operation today have the capacity to launch to higher orbits than LEO and only require extra fuel in the secondary launch stages to do so. This model assumes that there is no extra operational cost for satellites or space stations in MEO. By using the linear regression model, a range of launches can be predicted from now until 2050. Each of those launches would require extra fuel to be launched to various altitudes at MEO. The fuel burned in second stages to get to MEO is assumed to be fed at a stoichiometric ratio of one mole of liquid oxygen per two moles of liquid hydrogen. Liquid hydrogen is estimated to cost \$0.70/kg if its produced at the site of a rocket launch (Bonner, 2013) and liquid oxygen is estimated to cost \$0.21/kg (Miya, 2012). The final costs of extending all projected LEO launches to MEO from now to 2050 without a discount rate are shown in the table below.

Orbit Altitude (km)	Mass of Fuel (kg/launch)	Total Low Cost Estimate ($MM)	Total High Cost Estimate ($MM)
2000	19,711	$9.75	$12.24
2500	25,022	$12.38	$15.54
3000	29,291	$14.50	$18.19
3500	32,780	$16.22	$20.36
4000	35,671	$17.65	$22.15

Table 6: Costs of launching to various altitudes from 2018-2050 using regression projections

Discussion:

The additional fuel cost of moving operational satellites to MEO is exceptionally low compared to the cost of launching objects into orbit in general. The cheapest vehicle currently in use in terms of launch cost is the ArianeSpace Vega, which costs \$37 million per launch. The highest prediction of launches to the highest altitude would cost \$22.15 million for all launches from now to 2050 not discounted. The policy of excluding LEO for operational satellites clearly makes sense from an economic standpoint. Active removal missions are completely unjustified given that the more passive solution of simply launching higher is cheaper than even a single launch to actively remove debris from orbit. The cost of launching to any orbit is also likely to decrease over the next thirty years, even though this model assumes that it won't. The final cost does not include a discount rate, but could be far lower depending on the discount rate applied. No discount rate was used because the added fuel cost is relatively small compared to the cost of launch.

A key problem with this solution is the extra fuel carried on board each spacecraft, especially to move the satellite into LEO after its useful life. Carrying extra fuel is a hazard in case the spacecraft is hit with a piece of debris, which can cause an explosion. These explosions can trigger a chain reaction and create a cloud of smaller debris pieces. Extra care would have to be taken by debris observation stations to make sure satellites have as much advance warning about impending collisions as possible so that they can maneuver away safely. Added fuel would also pose a threat to national security, making military and communications satellites easier to bring down. Carrying additional fuel also requires additional fuel to carry the additional fuel. Plus the satellites launched must be capable of moving to LEO on their own at the end of life, meaning they must have bigger engines and, again, more weight in the spacecraft requires more fuel.

Mandating launches to MEO doesn't change the fact that the International Space Station (ISS) and all human spaceflight are still confined to LEO. The ISS would have to remain in LEO even as other satellites are launched to MEO. But even more concerning is the increased number of microsatellites, or CubeSats, that are being used. CubeSats have limited maneuvering capabilities and communications systems that do not function as well at high altitudes. Requiring launches to MEO counteracts the benefits of satellite miniaturization and would therefore be hugely unpopular with both national space agencies and private contractors. Not to mention it is physically impossible for a microsatellite to carry enough fuel to maneuver out of MEO as would be required by the policy. And a microsatellite in MEO could take as decades or even centuries to decay into the atmosphere once it runs out of fuel (Braeunig, 2013). Therefore this policy is incompatible with microsatellites.

It also deprives microsatellites of a basis for launch. One of the more attractive features of microsatellites is that they can fill the interstitial spaces in a payload carrying a more traditionally sized satellite. That way, when the payload is deployed, the microsatellites drift off with it. Under this policy, microsatellites could only be released in designated LEO launches or from the ISS. Therefore, a smaller number of satellites could be launched in each payload to MEO making the cost per satellite much greater.

Satellites that are launched to MEO would have to be built more robustly than satellites launched to LEO. Because the atmosphere is thinner, MEO has a higher flux of high energy solar radiation through it than LEO. All communications arrays and other vital electronics would have to be shielded against this. In conjunction with larger engines to conduct Hohmann transfers and added fuel, the mass of a satellite launched to MEO is significantly more than that launched to LEO. This means it fills more space in the payload of each launch and the rocket therefore cannot carry as many satellites compared to launching microsatellites to LEO. These costs would add to the cost of the fuel, making the policy of launching to MEO much greater than simply the fuel costs calculated here.

Officially designating LEO for end-of-life orbits only would require an international agreement, which most sources in the literature review say is not possible because a national could claim its right to access space over its need to comply with international policy. However, there are unofficial ways of reinforcing this policy. Insurance companies could offer lower rates for satellites in MEO as they are in a less risky environment. And since most launches today are done through the United States, Russia, and China, an implicit understanding among these three nations can greatly aid this policy even if it remains unofficial. Even private companies can be made to comply with this policy because they currently rely on using government launch sites like Kennedy Space Center or Vandenberg Air Force Base in the United States. Therefore the government of the United States could simply require private firms like SpaceX or Orbital ATK to comply with its guidelines for approved launch areas in order to use its facilities.

Even with the added costs of fuel, more robust satellites, and smaller payloads, launching to MEO still makes a great deal of sense as opposed to active removal. A great deal of the cost associated with launches are from getting through the lower atmosphere and so the cost of moving to higher orbits is by comparison very low. Most of the sources in the literature review advocated removing 5-7 large objects a year, which could cost as much as $350 million to implement every year. Therefore, using passive controls and launching to MEO instead, especially for satellites important to ground infrastructure, is a much better option.

Future Research:

This paper is only an attempt at putting a price tag on clean space. It's calculations are relatively limited as they do not account for the different types of spacecraft needed to reach and operate in MEO as opposed to LEO. The atmospheric decay calculations are also very rough estimates. Future research should focus on fine tuning estimates for when each piece of tracked debris will reach the atmosphere and verifying these against actual decay dates. The Hohmann transfer used in this paper also approximates transfer between two orbits that are roughly circular. It does not take into consideration highly elliptical orbits such as Molniya or Tundra Orbits. Such orbits are useful for servicing areas of high latitude and while they spend most of their time above LEO, their perigee is usually within LEO. Therefore, they must be accounted for by future models and taken into consideration by future policies on orbital debris.

Finally, this study can be refined by putting better estimates on all associated costs of moving to MEO. This paper focuses on the additional fuel to move a fully loaded Falcon-9 second stage to orbit. But there are other launch vehicles and other associated costs with even Falcon-9 launches. From the extra shielding required to house satellites in MEO to bigger engines to conduct end-of-life maneuvers, there are costs not well described in this study. More complete studies of this policy proposal should be conducted prior to implementation.

Recommendation:

Basic economics favors simply adopting MEO as the orbital range for operational satellites and using LEO as a disposal orbit. Budgeting just $10,000 for extra fuel in the second stage of each launch could guarantee enough fuel to both transfer into MEO and then transfer to LEO at the end of a useful satellite. This cost is not prohibitive because it is so small compared to launch costs. Even adding more robust satellite design and larger payloads, the cost is likely to still be reasonable because an increase of cost by a single order of magnitude is a justifiable expense over the next thirty years. Spending $500 million to make sure new launches are not impacted by debris and having a safe disposal plan at the end of a satellites life would still be a solid investment.

Even though passage of an international agreement to launch to MEO is not likely, it should still be proposed as a serious solution to manage orbital debris. In the meantime, the policy should be one of voluntary action. Launching to MEO would be an insurance against the dangerous effects of debris in LEO. In particular, satellites that are critical to national security or communication infrastructure should be launched into MEO and moved to LEO at the end of their useful life. Carrying this plan out will ensure that essential satellite infrastructure is safely out of the way of debris in LEO and keeps MEO as a clean space that future generations can use. Insurance agencies can help by offering lower rates for satellites going to MEO as an incentive to make use of the most debris-free space available,

Under this policy, launches to LEO would be discouraged, but not altogether banned. Private firms or developing space agencies that wish to deploy constellations of microsatellites may still launch to LEO with the understanding that LEO will become a more hazardous area due to debris. Launches to the ISS would still proceed as normal. However, deploying microsatellites in MEO would be strictly prohibited because they will likely remain in MEO for centuries before they decay on their own.

This leads to the two most crucial elements to successfully implementing this policy: proper assignment of debris responsibility and preservation of MEO. The latter is important because debris takes far longer to fall out of MEO than it does LEO. A broken satellite in MEO can take centuries to reach the upper atmosphere. Therefore, having a clear plan at the end of a satellite’s useful life is critical as objects cannot be allowed to stay in MEO. Microsatellites must be banned for this reason because they cannot move at the end of their useful life. If a satellite malfunctions and becomes inoperable, the owner of that satellite must immediately move to pull it out of the way of other operational satellites. Failure to comply could result in the lower strata of MEO being made into a more hazardous debris environment than LEO currently is.

The other piece that makes this policy work is assignment of responsibility. There is currently no legal definition for debris, and therefore no legal assignment of culpability for that debris. Even if international policy fails to assign LEO as a graveyard orbit only, it must come up with a definition for debris. Without it, nobody can remove potentially harmful pieces of large debris and there is no culpability. If for some reason a company like SpaceX were to go bankrupt, there would have to be a continuing liability for everything SpaceX has put into orbit.

Passive controls for orbital debris make more economic sense than active removal. As long as MEO can be established as a space for large, active, self-propelling satellites only, there is no need to worry about debris in LEO. All of our critical communication and security infrastructure can be kept safely above the crowded orbits of LEO. We are at a critical point where orbital debris is not yet a major international crisis, but it could rapidly go there if not managed properly. Any policies implemented now will set a precedent for how space is used in the future, and so great care must be taken. Space is undoubtedly necessary for mankind's continued survival. It will be useful for everything from mining for minerals that have grown scarce on Earth, to large scale agriculture to augment our arable land. As the common heritage clause stipulates, space should be protected for all generations. The establishment of a consistent definition for debris and its associated liability and proper zoning controls are the most efficient way to preserve our common heritage and protect the future utility of space.

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