2014-2015

Toulouse Business School

Active Debris Removal: A Business Opportunity?

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Executive Summary

In 1978, NASA scientist Donald J. Kessler demonstrated the danger represented by the decaying of man-made space objects in orbit around Earth. Indeed, if these space debris had been for a long time considered as an acceptable risk considering the low probability of collision, the ever expending activity of man in space skyrocketed the number of debris so much that the “Big Sky” theory is no longer valid. The 2009 the Cosmos-Iridium collision proved that the Kessler syndrome was not just an unlikely scenario. Scientists now fear that a new collision could cause a cascade of other collisions, denying mankind access to space.

Though mitigation policies are being put in place, it appears that the only sustainable solution would be to actively clean the near-Earth orbits. If for the last decade political, economic and legal obstacles have been slowing down the implementation of space debris removal, it appears that new initiatives in the fields of law, politics, industry and economical thinking are putting space cleaning under a new light. The development of such responsible activity seems to be possible as self-made ideas and geopolitical trends are evolving. It is the reason why through a thorough analysis of the literature available, we decided to demonstrate that not only the implementation of a space cleaning initiative was possible, but that it could very well become a profitable activity.

We first asked ourselves if a market existed beyond the need for ODR previously demonstrated. If today space pundits do not all agree on the exact answer, the school of thoughts underlines that LEO and GEO orbits are promising markets for space cleaning activities, LEO orbits appearing more as a public market and GEO orbits as a private market. Furthermore, in the course of our researches, we discovered that customers could potentially be interested by such projects. States could very well be willing to prevent their space assets from being destroyed by multiple collisions. For reasons linked to profitability, private companies such as satellite operators may want to use ODR technologies to remove objects from useful orbits or refuel their own satellites with propellant. Thus, we understand that more than just removing dead satellites, the development of space cleaning technologies can give birth to other services, such as space tugging, on orbit refueling and so on, that is to say that a new part of the space industry could emerge: On-orbit Satellite Servicing.

Eventually, we gathered and summed-up the various ways the literature sees to organize and implement orbital debris removal and associated technologies. Such industry would lie somewhere between a public good and a private sector service, between an international organization and a global market with enterprises

competing against each other. If initial funding should come from public funds, in the end the space cleaning industry may very well create its own profitability.

NB: This report is not a technical study, but tries to offer a comprehensive account of the main schools of thoughts regarding this subject. Thus, some of the data, concepts and ideas presented in the following pages were never tested nor validated.

Aknowledgement

We would like to thank Victor Dos Santos Paulino for reading draft versions of this paper. His help and his comments have contributed greatly to the quality of the final paper.

Introduction

Sputnik 1 was the first satellite sent in orbit around the Earth in 1957 by the Soviet Union. This launch ushered new political, military, technological and scientific developments that have allowed the development of the satellite industry. Five decades after Sputnik 1, space is congested, overcrowded and orbital debris pose an increasing threat to man activities in space. In fact, not only are our space exploration, scientific missions and satellite infrastructures at stake, but also are manifold communication and social infrastructures down here, on Earth. The shade of orbital debris could impact on 7 billion of human lives around the globe.
This threat was first expressed under the name of the Kessler Syndrome, theory proposed by .the NASA scientist Donald J.Kessler in 1978. Kessler showed that the density of objects orbiting the Earth is so high that collisions between objects could cause a cascade of other space collisions between debris. Those debris would render the space exploration and even the use of satellite impossible for many generations (Liou and Johnson 2006). This scenario could generate irrecoverable problems for the world's economy and stability. For example, as expressed by Johnson the "Global Positioning System (GPS) is one of our important technology which is possible thanks to satellites. "*GPS enhances our modern global economy; a failure in the system could disrupt emergency response services or cripple global banking systems*" (Logsdon 2001).
Of course, many specialists, scientists and engineers are trying to solve this issue, developing ways of de-orbiting space debris. However, major speed bumps are hindering those developments, and economics are considered as one of the major blockage. Indeed, as space debris removal is a costly activity that does not seem to bring any return on the value invested for its development, space actors are very reluctant to manage the issue. Nevertheless, for last five years, the literature on the subject is flourishing with essays on the potential value of space cleaning. This paper will try to give a comprehensive account of the main school of thoughts regarding this subject and will try to give some highlights on this ever going question: Is it possible to create sustainable value from orbital debris removal activities? And, if yes, how could we implement an economic/commercial structure dealing with such activity?

After assessing the actual situation on space debris and describing the dangers those objects pose, we will first explain what is today stopping us from developing ODR activities. But showing that several elements are pushing for its development, we will wonder if commercial activities are compatible with space cleaning, and if orbital debris removal (ODR) represents an actual business opportunity. Finally, this paper will give the reader a general survey of a potential ODR services structure.

Definition and Basics of Spaces Debris

Definition of Space debris according to the CNES: "*Space debris are man-made objects, including their fragments or parts, other than active space vehicles (or susceptible of use), larger than 10 microns and orbiting the Earth in outer space* ". In other terms, a space debris is a space object that is human-made and no longer functional, or a piece of this object. The sources of space debris are various, it could be debris from a mission or a collision between satellites. Based on the work of the NASA (2008), we establish that three countries are responsible for 95% of space debris : China (42 percent), US (27,5) and Russia (25,5).

Space debris are commonly classified into three categories according to their size:

- Untraceable debris. Their number is evaluated at around 300,000 and their size varies between one and ten centimeters.
- Debris larger than ten centimeters. Traceable and potentially avoidable.
- Debris smaller than 1 centimeter. There are more than 100,000,000 of those debris. Though they can damage spacecraft, and possibly destroy their payload or vital systems like TT&C instruments, they are not considered as being a cause for more debris.

Mitigation and removal strategies are used in order to reduce space contamination in orbit. The mitigation is the way to reduce new debris creation thanks to organization guidelines, taxes or law whereas removal covers the ways to remove debris with the help of deorbiting technologies, or operations aiming to move the objects to graveyard orbits.

I) Assessing the situation

In the movie Gravity (Alfonso Cuaron, 2013), astronaut Ryan Stone tries to survive in space after an orbital debris cloud strikes the space shuttle and the International Space Station. If today such a dramatic scenario seems highly unlikely, it is however possible that in a few years the risks linked to orbital debris increase dramatically. Indeed, spacefaring nations have been launching through the last decades an increasing number of spacecraft, especially in LEO, thus increasing the probability of space objects collisions.
This gloomy prediction was first theorized in 1978 by Donald J. Kessler, a NASA astrophysicist who gave his name to the Kessler Effect (also called Kessler syndrome, collisional cascading or ablation cascade). This theory can be summarized as follows:

“As the number of artificial satellites in earth orbit increases, the probability of collisions between satellites also increases. Satellite collisions would produce orbiting fragments, each of which would increase the probability of further collisions, leading to the growth of a belt of debris around the earth.” Donald J. Kessler and Burton G. Cour-Palais, *Collision frequency of artificial satellites: The creation of a debris belt*, 1978.

According to Kessler, the concentration of debris around the earth could prevent mankind from the use of space. To better understand the situation, let’s have a look on the figures:

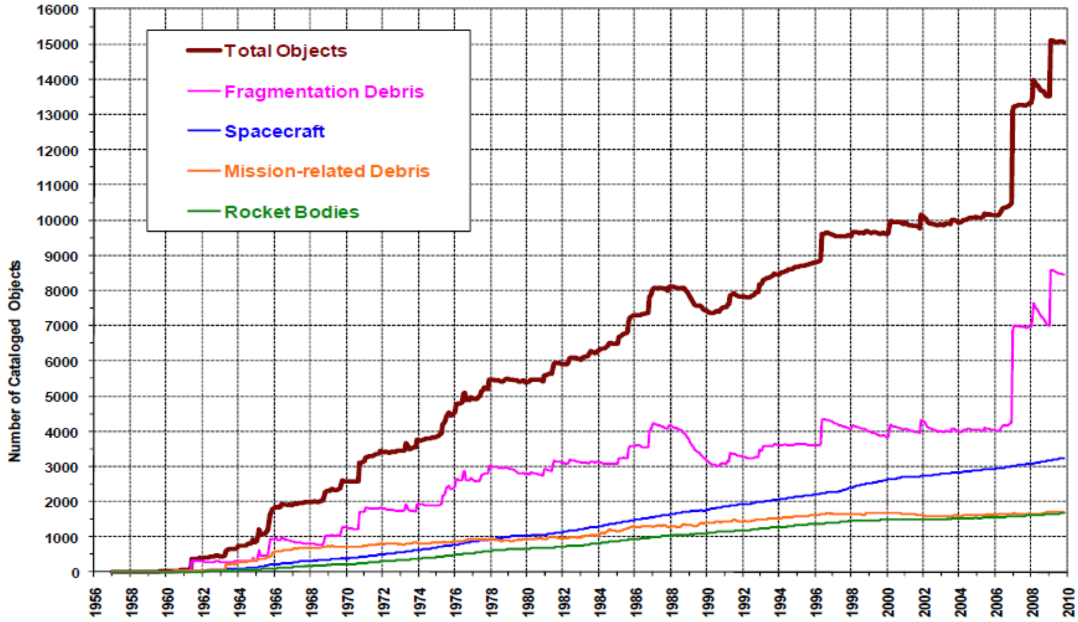

Figure Source: NASA/JSC, Orbital Debris Quarterly News, January 2010

As shown in this graph, the number of total objects orbiting around the earth (minus the 6,500 objects that are not reliably tracked or assigned to a parent launch) grew dramatically over the years, with a clear acceleration since 2006, due to two major breakups events: the 2006 FenYung destruction and the 2009 Cosmos-Iridium collision.

This growing number of debris is of course raising the probabilities of collision between two man-made space objects. In fact, according to Liou and Johnson (2006) and the various predictive studies used in their work, if humans do not take action to control the space debris population, an increasing number of unintentional collisions between orbiting objects will lead to the runaway growth of space debris in Earth’s orbit.

In fact, we are close to a breaking point. A NASA study stated by Liou and Johnson using predictive models demonstrated that even if all launches had been halted in 2004, the population of space objects in LEO with a diameter greater than ten centimeters would remain stable until 2055, that is to say until the Earth drag naturally deorbits those objects.

What are the risks? Well, such debris could completely stop us from using the space environment. The space debris population would become so large that the probability of impact between two objects would come close to certainty, becoming a major hazard for space actors, and mankind at large. Indeed, considering that those debris are orbiting the Earth at an average speed of 26,000 km/h in LEO, even an impact from a debris with a diameter lower than 10 cm could have dreadful consequences for a spacecraft, and even its protective shielding may not prevent the destruction, or at least the critical damages that would occur. In *Earth Orbit Debris, an Economic model* (Adilov, Alexander and Cunningham, 2013), Jack Bacon, a NASA senior executive in charge of ISS security states a 2009 event involving a space debris: "*With almost no warning, a small chunk from a [defunct] Cosmos satellite hurtled toward the ISS, coming within a mile of a direct hit. Due to its speeding-bullet velocity, even this fragment could have had an impact equal to that of a truck bomb. A ten-centimeter sphere of aluminum would be like seven kilograms of TNT".*

Then how should we deal with this problem? A few years ago, the probability of an impact between two spacecraft seemed so unrealistic that no policies were existing to tackle this issue. Indeed, the space environment was considered so large that scientists believed it was irrelevant to wonder about the future of the debris space missions left behind. The Cosmos - Iridium collision, that occurred in 2009 was the first of its kind, and demonstrated that the ever going "Big Sky" theory, stating that the space environment was so large that it was it was impossible that such an incident arises, was wrong. This Cosmos-Iridium incident proved that despite the vastness of space, we can no longer neglect the probability of a collision.

First, it seems that mitigation policies are not enough. Indeed, for the last decade, efforts to reduce space debris have focused on mitigation rather than removal. It goes without saying that mitigation efforts are important and are playing their role, limiting the proliferation of space debris, or at least curbing the augmentation of those debris in the near space environment. However, several studies show that those mitigation efforts won't be enough to stabilize the debris population orbiting around the Earth. In fact, according to Liou and Johnson, the various collisions between debris - that statically will happen - will create debris more quickly than the Earth orbital force can drag space decays. "*Yet, no active space debris removal systems currently exist and there have been no serious attempts to develop them in the past*." (Megan Ansdell, *Active Space Debris Removal, Needs. Implication. and Recommendations For Today's Geopolitical Environment*).
Prof. Dr Ram Jakhu shares the same view on mitigating measures. According to him, though those measures have a significant impact on curbing the rate of production of debris, the amount of space decays is so large that the scientific community, and space authorities in general, cannot wallow themselves in such limited procedures. In fact, Dr Ram Jakhu is going further, stating that "*taking into consideration that there is a massive amount of space debris already in orbit, it is clear that the time has come for active debris removal and on-orbit satellites servicing. This is necessary in order to meet the long-term need to protect the space environment as well as a short-term need to protect operating space assets from damage or destruction by debris*."
Prof. Dr. Ram Jakhu, Committee on the Peaceful Uses of Outer Space, United Nations, Vienna, Austria, 10 February 2012.

However, specialists agree to say that withdrawing the most dangerous pieces of debris would dramatically decrease the risks of collision:

"The best ADR strategy to meet this mission objective is to target objects with the highest collision probabilities and objects with the potential of generating the greatest amount of fragments upon collision." (Adilov, N., Cunningham, B. M., States, U., & Academy, N., *Earth Orbit Debris: An Economic Model.)*

Liou and Johnson's study concluded that "*only the removal of existing large objects from orbit can prevent future problems for research in and commercialization of space*" (Liou and Johnson 2006). Using its own predictive models they also noted that the European Space Agency (ESA) has come to similar conclusions. Nicholas Johnson from NASA's Orbital Debris Program Office stated in a testimony to Congress that "*in the future, such collisions are likely to be the principal source of new space debris. The most effective means of limiting satellite collisions is to remove non-functional spacecraft and launch vehicle orbital stages from orbit*" (Johnson 2009a, 2).
Going further, we are today able to precise which debris should be removed, that is to say the most dangerous of them: heavy debris (from 1,000 kg to 3000 kg), with specific orbital inclinations (between 70 degrees to 100 degrees in LEO)

How many objects should we remove? Well scientists and specialists seem to agree that an average of 5 to 10 debris removed would significantly reduce the risks of collisions (even though it would not completely elude this risk). It is the point of Megan Ansdell in *Active Space debris removal: needs, implications and recommendations for today's geopolitical environment*. She states a NASA study that "*simulated active debris removal over the next 200 years showed that certain pieces of space debris are more dangerous than others, in that they are more likely to cause debris-creating collisions. [...] The study found that annually removing as few as five of these objects will significantly stabilize the future space debris environment.*" (Megan Ansdell).

During this part of our paper, we demonstrated that the issues related to space debris were extremely serious, even though the space community is only starting to acknowledge the urgency of the situation. We all showed that the dangers that represent space debris are not unavoidable if the space authorities start acting to solve it. Indeed, removing as few as 5 to 10 satellites from orbit per year could reduce significantly the debris population.
Nevertheless, nothing seems to be undergoing for the development of space debris removal. Indeed, various barriers are stopping the progress in this field.

II. Obstacles and opportunities to Space Debris Removal.

NB: This part will not deal with the technical challenges related to this subject as it is not the purpose of this paper.

II.A) Obstacles are on the way.

The 2009 Cosmos-Iridium collision challenged the Big Sky ideology – arguing that space was so big we could use it without constraints – and demonstrated to scientists that space was not infinitely exploitable. *"Nowadays, space debris seriously threatens sustainable use of space, as it is considered to become a major navigational hazard to operating satellites"* (64th International Astronautical Congress).
However, and despite the urgency of the situation, many obstacles are lying on the way of an orbital debris removal solution. Indeed, not only the clear lack of legal background is preventing authorities to act, but also a myriad of political and economic obstacles need to be overcome to protect the near-Earth space environment.

1) A clear lack of jurisdiction.

Since the first steps of mankind in space, spacefaring nations have established agreements in order to create a juridical framework for the space conquest and the space industry.
The Outer Space Treaty, ratified in 1967, forms the basis of space law and gives the first principles for governing the activities of States in the exploration and the use of outer space. In 1972 the Space Liability Convention, dealing with the eventual damages caused by space objects, started including space debris in its scope, thus expanding the former treaty. One of the main principles of this convention is that "*States are internationally responsible for all space objects that are launched within their territory [...], and then States are fully liable for damages that result from their space object".* In other words, nations are responsible for their actions and potential damages that they can cause in the space environment. It means also that the consent from the country owning a spacecraft is mandatory to remove the aforementioned object, may it be from a private or a public ownership. Indeed, the Outer Space Treaty specifies that "*countries are responsible for the outer space activities of both sides, their governmental and non-governmental entities*".
However, despite all these measures written to create a jurisdiction regarding space activities, the clear lack of a comprehensive definition of space debris remains a major issue for the development of an active debris removal solution. Indeed, even if the United Nations Committee On the Peaceful Use Of Space (UNCOPUOS) implements a new definition for space debris, we observe that the definition is too evasive. For instance, according to the IAA Cosmic Study on Space Traffic Management *"no legal distinction is made between valuable active space-craft and valueless space debris."*
In fact, international organizations did not even take into account the fact that some space debris may not have an assigned launching state. According to Paul Kallender -Umezu in *A Market for Cleaning Up Space Junk ?*, "*Neither the Liability Convention nor the OST cover who is at fault if a third party disturbs a piece of debris, which explodes and later collides with another satellite, or who is liable for a removed debris object that lands on a house, private property, etc*."
Eventually, it seems that the lack of definition and details of international laws regarding space debris makes it impossible to identify removable objects and to actually create a legal framework that would manage ODR operations and deal with space disputes.

But as we will explain it in this second part, the fragility of space laws is not the only issue in this matter.

2) Political Issues.

As space activities are an extremely sensible matter on the international ground, since they involve military operations in sort of an unregulated space, there is no wonder that for the moment, space fairing nations never succeeded to reach an agreement on space debris.
Several questions are pending on this matter. First of all, as we already mentioned it, space activities involve dealing with sensible and sometimes secret technologies. Earth observation satellites and communication satellites are sometimes used by states for military purposes. Some of them are not even declared as such, and it is not rare for a launch services company to send in orbit unidentified spacecraft. Thus it is easy to understand that states are not willing to see the development of technologies allowing a spacecraft to get close to another one and to manipulate it or worst – moving it from its current orbit. As a spacecraft designed for on-orbit services or for space cleaning could as well be designed for antisatellite operations, many countries are slowing down the development of such devices, and are reluctant to cooperate with other nations, fearing that this newly developed technology may one day be turned against them.
For example, the US International Traffic in Arms Regulation, or ITAR, prevent any nation from manipulating any object with a potential military use without the agreement of the US government if this object or if one of its component is made from American technologies. In that case, it is easy to understand that ITAR regulations can reach a large part of the world's on-orbit satellite fleet. As such, the ITAR regulations are considered as one of the main political obstacles for an effective orbital debris removal.
Also, even if it seems that every nation wants to get rid of space debris, as they are disturbing their space activities, no nation yet declared to be willing to pay for what will be a costly ODR operation. For example, many small nations owning only few spacecraft (or even no spacecraft at all) are claiming that the big polluters, mainly the US, China and Russia, should pay for such cleaning. But on the other side, even a country with no satellites is benefiting from services issued by foreign companies, owning foreign satellites. As space appears as a common good, shouldn't every nation pay? For the moment the question remains unanswered. In fact, space cleaning operations will be all the more costly as countries keep being reluctant to a common solution. As expressed by Liou and Johnson (2006), the lack of cooperation is leading to a cost inefficiency due to the uncertainty and complexity of the technology. *"International cooperation in space has rarely resulted in cost-effective or expedient solutions, especially in areas of uncertain technologies feasibility".* Liou and Johnson, 2006.

3) Economic obstacles

Space is considered as a common good and is unfortunately overexploited by humans. It is the consequence of what Garrett Hardin called in 1963 the *tragedy of the commons*, a state of over-exploitation due to the impression that the resource is infinite. *"Space suffers from the tragedy of the commons, a phenomenon that refers to the over-consumption of shared resources when there is no clear ownership over it"*. By this sentence, Megan Ansdell means that the natural tendency of space actors in power will likely be to do nothing until they absolutely must. Similarly to the case of global warming, space authorities tend to wait as much as possible before taking any action, waiting for the situation to become critical. Why that? Well, the development costs of space cleaning technologies are so high that most authorities will only be ready to spend this money when they are compelled to.
According to NASA's Advanced Space Transportation Program, it costs around $10,000 per kilogram to launch anything to orbit. In fact, the contribution to implement a viable ODR is evaluated at a cost of $100-200 million per year according to some business cases. To put that figure into context, it represents less than 1% of the world annual public space budgets. However, Governments are still reluctant to spend this money that could preempt severe space collisions and generate billions of dollars of losses.

As we just saw it, numerous obstacles are slowing down the efforts made to conceive an efficient ODR policy. However, several events prove that progress has been made on the path during the last decade.

II – B) New opportunities for ODR.

Despite all the setbacks and barriers that are slowing down the development of an efficient ODR policy, several breakthroughs in this matter are proving that the idea of an ODR action is making its path in the space community. Spacefaring nations and the scientific community are more and more understanding the need for taking action as soon as possible. Indeed, several initiatives have been launched in the last decade, and new are on their way.

1) A new jurisdiction is being created.

First of all, in 2007 the Inter Agency Debris Coordination committee (IADC) and the United Nations Committee on the Peaceful Use of Outer Space (UNCOPUOS) adopted guidelines and promoted various measures in order to draw a first international space debris mitigation policy, focusing on the reduction of the rate of new debris generation. Even if those guidelines are non-binding, meaning that no nation is forced to apply them, they represent a first step toward an international agreement on ODR. Such international decision constitutes an important push for space cleaning. According to Prof. Dr. Ram Jakhu, from the UNCOPUOS, "*National policies, laws and regulations can facilitate the conduct of active debris removal and on-orbit satellite servicing activities. For example, Canada's Remote Sensing Space Systems Act contains provisions regarding systems disposal*." , (Committee on the Peaceful Uses of Outer Space, United Nations, Vienna, Austria, 10 February 2012.).

Regional and national guidelines are also being implemented. In 2002, in the aftermath of the IADC guidelines, the European Space Agency (ESA) wrote its European Space Debris Safety and Mitigation standards. Then the ESA developed its own Requirements on Space Debris Mitigation for Agency Projects, in line with the IADC guidelines. Later, in 2010, the European Union drafted a Code of Conduct setting up a comprehensive amount of guidelines to minimize debris generation, which , according to Paul Kallender-Umezu, *"could become the basis of an international soft law regime.*" (*A Market for Cleaning Up Space Junk?*, May, 2011). Further East, in 2006, the Chinese Space Agency released a white paper in which it stood for debris mitigation policies at the transnational level. That same year the U.S. National Space Policy reiterated its will to minimize the creation of space debris (James E. Dunstan, Bob Werb, International Conference on Orbital Debris Removal 2009) and went further than the 2007 UNCOPUOS guidelines, declaring that all entities needing an Federal Communication Commission (FCC) license had to provide the FCC with a debris mitigation plan in order to get the licence.*

The International Standards Organization (ISO) developed in 2011 a new label, ISO 24113, regulating space debris mitigation requirements. This label tries to standardize the way how mitigations measures are implemented. The European Cooperation on Space Standardization (ECSS) adopted ISO-24113 in the space sustainability branch.

2) Promising industrial projects are being launched

Industrial projects that are being launched prove that the development of space cleaning technologies is possible and promising. That is the case for a 280 million USD project initiated between MacDonald Dettwiler and Associates Corporation (MDA) and Intelsat. MDA, a satellite manufacturer, was to develop a satellite able to refuel and service other satellites already in orbit. Intelsat, the world's largest satellite operator (with a fleet of 50 operating satellites) was then supposed to invest in this project. Even though the agreement was cancelled in 2012 for various reasons (*Spacesafetymagazine.com*, Joel Spark, january 20th, 2012.), this very serious proposal could have given birth to satellite servicing technologies that could have been used for deorbiting operations, proving that industrial actors could develop and launch such spacecraft. Other projects are on-going: Ecole Polytechnique de Lausanne and Andrews Space are developing two separate projects to launch cubesats that are to deorbit other cubesats in LEO.

Furthermore, national space agencies are also working on technologies that could - directly or indirectly - be used for ODR. On the American side, various governmental projects could lead to an ODR capability. The NASA's Robotic Refueling Mission experiment that aims to demonstrate robotic refueling, with as a final objective to kick-start in the US a commercial orbital servicing activity. A second project, being currently developed by the DARPA and named Phoenix program aims to develop a demonstrator spacecraft that would harvest parts of dead GEO satellites to reuse them on other systems. On the European side, the most promising project according to Paul Kallender-Umezu is a German work on an orbital servicing mission. In 2010, the German Space Agency DLR started to work on on-orbit servicing demonstration, called the Deutsche Orbital Servicing Mission (DEOS).

2) Cost effectiveness

Despite ODR heavy apparent costs, political and industrial decision makers need to think about the cost effectiveness of an active orbital debris removal activity. Indeed, even if the figures vary largely depending on the source, space analysts agree on the fact that the cost of implementing and solution to space debris will be way cheaper than the cost of doing nothing. For example, as underlined by Darren McKnight in *Pay Me Now or Pay Me More Later: Start the Development of Active Orbital Debris Removal Now*, removing 20,000 cm-size debris from LEO would cost around 10 to 70 million dollars. To get an idea of comparison, the loss of the $150 million (plus $80 million lunch cost) Orion 3 satellite in 1999 cost insurers $265 million dollars, a cost to which need to be added 645 million dollars in revenue losses. According to D. Pelton in *A Global Fund for Space Debris Remediation: A New Way Forward to Address the Mounting Space Debris Problem*, in order to achieve an effective cleaning of the near-Earth orbits, all satellite operators would need to invest 5% of the total mission cost of all their missions. Considering that those operators invest between 6 and 20% of the mission costs in launch insurance, 5% of the mission costs do not seem so much to prevent massive collisions. The challenge would of course to convince satellite operators to spend this money to avoid what is considered an unlikely danger.
Furthermore, Political and industrial powers need to understand that time is also playing against us financially speaking. As Donald Pelton highlights it, "*delays in the attacking serious common global problems—whether it be climate change, ozone layer depreciation, or orbital debris buildup will only become more difficult, more technically challenging and certainly more expensive."* (*A Global Fund For Space Debris Remediation : A New Way Forward to address the Mounting Space Debris Problem).*

Conclusion:

The purpose of this paper is to discuss the possibility of creating a sustainable business activity originating from the issue of space debris, an issue that at first appeared as dead-end. Indeed, the cost of the possible solutions, the defiance of the various governments regarding on-orbit services and the lack of juridical background is stopping space authorities and industries from cleaning the space environment. Nevertheless, we demonstrated that despite all those road bumps, several initiatives are enlightening the path toward sustainable ODR activities. Several breakthroughs in the jurisdiction are pushing toward new possibilities regarding space laws, and even governments are starting to tackle the issue of space decays. Finally, innovative projects are paving the way for new industrial solutions.

The following chart gives a comprehensive sum-up of the pros and the cons of the creation of a possible ODR activity:

ODR constraints	ODR opportunities	External Readiness
Lack of clear jurisdiction: No definition of space debris, impossibility to hold any entity responsible for debris.	**New national and international initiatives are on-going:** At the international level as well as on the national level. Furthermore, new standards are being created. This trend is expected to continue.	+ +
Political mistrust and constraints: Fear of seeing an ODR device turned into a weapon or a spying spacecraft.	**Internationalization of the issue and urgency of the situation:** Since orbital debris is a threat to every satellites, whatever their nationality, an international answer could be expected.	−
Technological constraints: There has never been for the moment any demonstrator for ODR operations	**Technological breakthrough:** The technology exists and several projects are on-going.	+ + +
Cost: Development of ODR spacecraft is very expensive.	**Cost of losing a satellite:** this cost is higher than the investment for ODR spacecraft.	+

In conclusion of this second part, we can then assume that the environment surrounding the removal of space debris is becoming more favorable for the development of the activity, though political aspects remain a major threat for it.

Eventually, a lot of new promising projects and proof of good will from governments are on-going. However it is still not enough to launch the process of creation of an ODR. Could the market trigger this ODR by attracting investors on projects? Or should the government tackle the issue directly before turning it into a commercial activity?

III) Orbital Debris Removal: a business opportunity?

We demonstrated that the external environment was favorable for the development of ODR services. However for the moment no enterprise is doing business on this activity, mainly because of the obstacles we studied in the previous part. Nevertheless, now that we understand those obstacles can be overcome, we want to figure out if the removal of orbital debris could become a viable business activity. We will try to give a comprehensive overview of the main schools of thoughts regarding the questions this subject poses.

1) Is there a market?

The first question we should ask regarding our subject is the question of the existence - or not- of a market for commercial ODR services. Regarding this thorny issue, specialists disagree. According to Paul Kallender-Umezu, "*the first question [...] is: Is there a market? The answer for GEO is a qualified yes. The answer for LEO is probably "no" for purely commercial ventures*." (May, 2011).
However Emanualli, Chow, Prasad, Federico and Loughman seem to think otherwise. Indeed, according to the authors of *Conceptualizing viable ADR Option* (2013), GEO satellites are less interesting as targets for a deorbiting operation since they are orbiting at lower speeds than in LEO, because the GEO area is much wider than the LEO area is, reducing probabilities of an impact between two spacecraft and because GEO satellites still have the option of leaving the GEO belt to lose themselves in sort of a "satellite graveyard", a quasi-non-decaying area outside of the GEO region that poses very little threat not worthy worrying about. "*Therefore, threats from orbital debris are greater in the LEO region due to a combination of high debris concentration, large number of crossings and high relative velocities.*" (Emanualli, Chow, Prasad, Federico and Loughman), and in that case cleaning the LEO region seems to be more important and a more pressing matter. Another argument could advocate for a LEO focus in the cleaning of space junk: LEO is a much closer orbit, so it could be easier and cheaper to operate there. However, we need to consider the fact that it is easier to remove GEO satellites considering that orbit planes are much closer: The requirements for large plane changes in LEO in order to perform multiple object retrievals may also add to the costs of LEO systems whereas total plane changes (for inclination) are limited to a maximum of 15 degrees in GEO.
Moreover, regarding the satellite graveyard issue, even if the possibility exists, we need to admit that operators are rarely willing to use precious propellant to dispose properly of their spacecraft when they can only leave it where it was. In Paul Kallender-Umezu own words: "*As of February 2010 there were 1,238 known objects in the GEO belt, of which only 391 were under some level of control; of these 594 were drifting; of the 21 GEO satellites reaching End of Life (EOL, see below) in 2009, only 11 were disposed of properly.*" (*A Market for Cleaning Up Space Junk?* Paul Kallender-Umezu, May, 2011). Thus the non-willingness of operators to dispose of their spacecraft in GEO increases the risk of space collisions between spacecraft.

Even if the question of which orbit to service is not completely answered yet, there are many incentives pushing for the development of such activities:

- Risks of losing the satellite.
- For GEO satellites: dead sat are using a spot on the GEO orbit that could be useful to operators.
- Cost of moving a satellite to avoid collision (use of propellant, thus life span is reduced and operators lose money on their investment). "*To cope with this, operational satellites are increasingly forced to maneuver around debris to avoid collision; some 100 collision avoidance maneuvers have been performed to date, most occurring since 2008*" *A Market for Cleaning Up Space Junk?,* Paul Kallender-Umezu, May, 2011.

Finally, we can assume that there is no defined market at the moment, but we can see a clear need for ODR and associated services. As seen earlier in this paper, the number of projects that are being developed prove crucial creating a commercial market for ODR services. NASA seems already ahead of those initiatives. In a landmark report written by the Goddard Space Flight Center, the US space agency concluded that *"there are large classes of commercial satellites that could be economically viable to service" (On-Orbit Satellite Servicing Study Project Report, NASA, 2010).*

2) Which customers should a commercial ODR target?

It is a very important question with no definitive answer. Surely State entities will be interested in such offer. Indeed, States are using satellites for many purposes, especially in the defense area. Considering the price and the strategic asset of a military satellite for example, it is easy to understand that states are not willing to let those pieces of technology destroyed.
Furthermore, and maybe more importantly, satellites provide numerous public services, such as telecommunication, meteorological data, internet, etc. Yukihito Kitazawa (IHI Corporation) declared during the international interdisciplinary congress on space debris remediation, (2011) that "*GPS, weather satellites, EO satellites and other spacecraft already form social infrastructures, which give great benefits to the world, not only to the space countries*". The loss of those spacecraft would be catastrophic for our society.
According to a business case on ODR produced by the Delft University of Technology in 2010, private operators would not be willing to pay for an ODR, considering that revenues from this activity are not existing in the near future, and appear unclear on a long term view. Thus, it seems that the main customer for such activity would be the public sector. "*In the cluttered LEO orbits, the public sector has an intense interest in debris removal, and securing future access to space. Many of the satellites in LEO are owned by governments and public organizations. [...] Additionally, space-faring nations have an obligation to resolve the LEO debris problem to clean up space for greater public good*." SpaceTech, July 2010.

But States are not the only one that could be interested in such services. Private companies could be incline to use servicing capabilities to deorbit satellites in GEO, in order to free some very valuable orbital slots on the GEO belt, or also to service their own satellites, thus extending their life time. As explained in the Retrospace

Business Case (Delft University of Technology), "*In contrast to LEO, commercial operators are interested in debris removal at GEO as that is where the high revenue commercial satellites reside. Non-operational satellites blocking valuable GEO slots are excellent candidates for "space tug" services which can tug these dead satellites to a GEO graveyard orbit".*

3) What type of offer could a private company propose regarding the field of ODR and OSS activities?

We can imagine several ways a company could do business in the field of ODR services. Some of the followings are already being tested; others are purely fictional but could in the future become actual business activities.

- The main activity would be of course the removal of decaying space objects. As explained later in this paper, we believe that states or companies would be interested in cleaning the space environment.
- On orbit services. This activity itself covers various services:
  → the main one would be the provision of refueling services in order to extend the mission life of a spacecraft. As explained by Prof. Dr. Ram Jakhu, "*on-orbit satellite servicing offers short-term benefits by way of mission life extension through refueling and assurance that the operator can meet post-mission disposal requirements. Life extension directly affects income for commercial systems and extends capabilities for government satellites. Thus, there may be a business case for implementing on-orbit satellite servicing.*" Prof. Dr. Ram Jakhu, Committee on the Peaceful Uses of Outer Space, United Nations, Vienna, Austria, 10 February, 2012.
  → Damage inspection services: companies or space agencies could be willing to pay to get information on the damage status of their spacecraft. It could also be used for analyzing failed launches or failed orbital operations, and in that case it could become an interesting service for insurance companies that may want to know why the mission failed before paying insurance coverage.
  → Space tugging: It is the example of the ViviSat mission life extension program. A spacecraft could tug another one if it failed to reach its correct orbit. It is sort of a derivative from the concept of space refueling.
- Also the mission prime developing the ODR spacecraft or the company managing them (in case of a company) could also choose to directly sell the spacecraft to states or other companies, as a usual satellite manufacturer would do.
- Emissions trading (similar to CO2 trading): As we do today with CO^2 emissions, a business opportunity could be the trading of space debris emissions in the case of the creation of a debris emission tax, as we will explain later. Like in regular trading, the company could take a percentage of the sales of emission rights.
- Launch debris cleaning : Other customers for a private company could include launch service providers, who have an obligation to de-orbit their upper stages,

More importantly, as this list of potential activities prove it, the development of ODR servicing activities is expending the field of space services possibilities. More than just focusing on the removal of space objects, ODR technologies could very well give birth to a new and larger type of servicing: On-orbit servicing. ODR activities prove that way they can become a complete industry, developing its own new streams of revenues.

Considering the information we previously reviewed, we can assume that there are business opportunities in ODR services. However, we did not answer the question of the organization of this ODR activity. Indeed, if those opportunities and incentives for acting for an ODR solution seem to be strong enough to push mankind to tackle the issue of space debris, we should wonder under which structure such an enterprise should be dealt with. Are we going to attend the birth of a new international space agency for ODR, ruled by the international laws, or is it the beginning of a new free market, where enterprises compete against each other to gain orbital debris market share?

IV) How should this ODR activity be organized?

In this part of the research thesis, we will try to draw potential the structure of an efficient ODR system. Note that some of the ideas contained in this part were never tested nor validated.

Who should take care of the organization, or at least the first steps of an innovative and efficient ODR solution? This first question alone is considered to be a thorny issue on different levels. The first level of inquiry we will try to enlighten is the issue of nationality. What should be the nationality of the body in charge of cleaning space? The US? Russia? The EU? Or to contrary, should it be an international entity, under the form of the UN? The second question arising is the following: what should be the type of entity that will take the burden of the ODR? Indeed, while some specialists believe that state entities are the only one able to take the charge of massive investments to develop ODR solutions, other theorists advanced that private entities, such as industrial corporation are more fit to the task.

1) What should be the nationality of the institution developing the ODR - if a specific nationality is more appropriate?

As stated earlier, 95% of all space debris was produced by only three nations: the US, Russia and China. In that case, it would seem logical and fair that the work and related expenses linked to space cleaning should be taken by those countries. However, as Megan Ansdell highlights in her essay *Active Space debris removal: needs, implications and recommendations for today's geopolitical environment*, most of the world's countries are benefiting from the satellites sent in orbit by the aforementioned states. In that matter we are facing a "free rider" problem that is complicating the situation. The fairer decision would be to make each state of the world paying proportionally to their use of space, which is of course barely imaginable since it is impossible to evaluate the amount of use of space by country.

Nevertheless, several theorists and scholars believe that the most appropriate solution would be the development of an international organization, basically like the UN. Some argue for such an international structure, and stand for an International Economic Fund for Space Debris Removal. It is the point of view of Donald Pelton, who believes that forcing the States that are considered to be responsible for the creation of space debris to act and clean the near Earth space environment really isn't the solution. On the contrary, Pelton stands for the creation of a "*Global Economic Fund for Space Debris Removal*, consisting in the agglomeration of various space-related entities able to develop the technologies needed to perform this ODR. According to him, those licensed entities – rather than a single international agency – would be compensated by a fund which structure would give more agility and competitiveness.
Prof. Dr. Ram Jakhu from the IAASS Legal and Regulatory Committee promotes such a solution, with a structure that could be inspired from the X-prize model. He underlines that since satellites are part of a social structure benefiting to everyone, *"it is only fair and equitable that all who are involved in space development – either directly by way of utilization or indirectly by way of deriving benefits therefrom - cooperate internationally in an effort to find appropriate mechanisms for the conduct of active debris removal and on-orbit satellite servicing"*. And, trying to divide the costs fairly between all the parties involved, Prof. Ram Jakhu suggests that all space actors should contribute equally in proportion of their actual share of the global launch and space operations activities.

However, not everybody agrees on the question of an international organization. For example, Megan Ansdell suggests that the urgency of the space debris issue do not advocate for an international solution (since it is most of the time longer and more complicated to put in place this type of structure. In her own words, she states that: "*given the need to start actively removing space debris sooner rather than later to ensure the continued benefits of satellite services, international cooperation may not be the most appropriate mechanism for instigating the first space debris removal system*." Megan Ansdell is actually pretty direct arguing that the United States should take the lead on space cleaning and start now developing spacecraft able to remove the most dangerous objects. Indeed, despite the costs this technological development would involve, taking action would not only reinforce US leadership in space, but would also insure long-term benefits to the country by keeping the space environment clean. Anyway, whatever the reason for the US to take the lead on this matter, US leaders should keep in mind that they have a lot of interests in protecting their near-Earth space surroundings, as "*the ability to access and utilize space is a vital national interest because many of the activities conducted in the medium are critical to U.S. national security and economic well-being*" (U.S. Department of Defense 1999, 6).
Paul Kallender, is to the contrary recommending that Switzerland should be leading and implementing the first steps of an ODR organization, as its neutral government eludes various geopolitical issues. Emanuelli, Chow, Prasad, Federico and Loughman suggest the same thing, arguing that since "*Switzerland is not a spacefaring country; it looks like it could be a suitable country to start active debris removal initiatives, which deal with security and complicated legal issues*."
Conceptualizing viable ADR Option, 2013

2) Should the ODR be managed by the States only or by private entities?

It seems that it will not be possible to act without the support and help of private companies. Indeed, commercial entities involvement would stimulate the emergence of a market and a competitive environment. It is at least the point of the 2010 NASA *On-Orbit Satellite Servicing Study Project Report* where the Goddard Space Flight Center recommended partnership between government agencies, the industry and academia to pursue the development of an ODR/OSS industry. Megan Ansdell is also supporting this view, stating that she believes that having multiple companies developing solutions would create competition, reduce the costs for the state, accelerate the problem remediation and trigger the development of various solutions that would address different problems, for example spacecraft for different orbits. M. Ansdell also adds that the use of Public-Private Partnerships would foster the launch of early investments that would "*give the United States a head start in what may become a critical industry over the coming decades.*"

In fact, it is yet pretty difficult to assert which country will participate in this space cleaning, and who exactly will do it. On one hand, space cleaning should be a concern for everyone, so it seems logical to think that every country should participate. At the same time, not everyone is responsible for space debris, and mostly not everyone has the capability - or any interest - of acting for an ODR solution.
In the end, this situation is well summed up by Emanualli, Chow, Prasad, Federico and Loughman:

"*Much like waste management on Earth, cleaning up space junk will likely lie somewhere between a public good and a private sector service. An international, cooperative, public-private partnership concept can address many of these issues and be economically sustainable, while also driving the creation of a proper set of regulations, standards and best practices*." *Conceptualizing viable ADR Option*, Emanualli, Chow, Prasad, Federico, Loughman, 2013.

3) How should we finance space cleaning?

As explained earlier in this paper, space debris are the consequence of a standard "tragedy of the commons". Since users of space do not pay the full price for its use they tend to overuse it. The world's nations can't always agree on how best to handle clean-up. Current international guidelines for debris mitigation are largely voluntary, with some agencies — like NASA — more careful than others. Everyone has an incentive to keep launching satellites into space. The incentives to tide up the aftermath are weaker. Economists typically solve this type of problem using what is called a Pigouvian tax, sort of a user fee that tends to align incentives to limit overconsumption. According to the theory of Arthur C. Pigou in his book *The Economics of Welfare*, *"a tax can be applied to a market activity that is generating* *negative externalities. The tax is intended to correct an inefficient market outcome, and does so by being set equal to the negative externalities".*

"*User fees are a solution straight out of the Reagan era to deal with precisely these sorts of environmental issues*" says Peter J. Alexander, an economist at the Federal Communications Commission and a co-author of *Conceptualizing Viable ADR Option* (2013).

In *Earth Orbit Debris: An Economic Model*, economists Alexander and Cunningham, along with Nodir Adilov of Indiana University-Purdue University, propose a solution: Countries should impose a fee or tax on orbital launches. The fee would be set high enough that companies and nations don't over-populate space with objects. And the revenue could fund clean-up efforts. This, they say, would be preferable to the current system of ad hoc rules and regulations on space debris.

That said, a user fee would create its own set of headaches. How does the tax get divvied up? As we previously explained, most of the debris currently in space, after all, was put there by the United States and Russia, with China a close third. Should those three countries shoulder most of the burden or should we consider that space, as a common good benefiting directly or indirectly to all, should be cleaned up by everyone?

According to an interview of Alexander by the Washington Post (October 23rd, 2013), there is no definite answer but "*the bargaining environment here has become incredibly complex. [They] looked at the simplest solution, which was to impose a launch fee on a forward-going basis*." Indeed, the solution could be a tax on satellite launches in order to finance ODR and compensate the negative externalities of the space debris contamination. Therefore, it will impact all the parts of the space value chain. The practical problem here is to agree on who will pay the tax. But usually we observe that the fee is often supported by the final users, i.e. the average consumer.

Many ideas are emerging regarding such tax. For instance, Hames Dunstant the Founder of Mobius Legal Group has suggested to create a smartphone tax, a $1 tax on the GPS chip in smartphones could be the source of Space Debris Removal. Furthermore, a system of tax trading could be created, similar to the CO^2 emissions trading system. If a satellite operator creates debris launching its satellite in orbit, the tax would normally apply. However, if this launch is not creating debris, the operators could trade this "free debris space" with other operators who are producing debris. Also, as underlined by Yukihito Kitazawa from the IHI Corporation, the tax could be indexed on a hazardousness index and ISO standards so it would not prevent small space countries from developing small satellites missions. Eventually, it appears that in the case of space debris, national governments will need to be the "grown-up in the room" that first act to create the initial funds.

4) How should we organize the distribution of money?

As discussed earlier, many specialists gave thought to this question and one of the most recurrent models appearing in the school of thoughts is the principle of an international fund for space debris.

Donald Pelton stood for this option, arguing that "*the benefits are that a diversity of "international licensed entities" can develop the needed technology; these entities would be compensated only after they have successfully developed needed* *technology and removed debris from orbit; the creation of a fund rather than a single international agency charged with this task insures flexible & competitive development of technology; this allows the fund to be shut down when the mission is accomplished as opposed to shutting down an international agency*".

It is also the solution presented by James E. Dunstan and Bob Werb during the International Conference on Orbital Debris Removal (12/08/2009, Reston). In this scenario, they stand for the creation of an Orbital Debris Removal and Recycling Fund, in charge of identifying Orbital Debris, establishing criteria for ODR, Assisting companies with re-registration, verifying action and paying out for successful ODR. Satellite operators would pay a tax to their respective states, which would then pay into the ODRRF based on threat criteria of new launch. The ODRRF would then organize the debris removal operations paying private companies that would remove debris.

This option seems viable as its price represents according to D. Pelton only a small part of the launch price. *"The money to capitalize this type of space debris fund would be collected prior to all launches and would equivalent to perhaps 5% of the total cost of various space-relocated missions"*. (D. Pelton).

Conclusion:

In this paper, we tried to give a comprehensive account of the various schools of thoughts regarding how to tackle the space debris issue – if not danger. Our final goal was to underline that space debris could be considered as a business opportunity. Is it possible or not to put in place a revenue stream issued from space cleaning? As space cleaning activities are, on the short to medium term, not apparent sources of revenue, the obvious answer would have to be: "no, there is no potential sustainable business possible in the field of space cleaning." But as we try to overcome those self-conceived ideas, we discovered that a structure involving the governments of space faring countries, space industries, insurance companies, satellite operators and all the other stakeholders of the space value chain could potentially give birth to a sustainable space cleaning business. With money issued from well-conceived and legitimate taxes, collected by an international – or at least multi-national – fund organized by major space authorities, space industries could develop new technologies, new spacecraft able to service decaying satellites. In fact, more than the creation of a new business, the gathering of means trans-nationally in order to solve the common issue of space debris could very well give birth to a complete new stream of activities, that not only focus on space cleaning but that could be part of a much bigger part of the space industry: the on-orbit servicing. "*On-Orbit Satellite Service will accomplish logistic support, refueling, supply coolant and consumables, rescue from stranded situation (trouble in deploying antenna, solar paddle, etc.) and also on-orbit assembly and maintenance of large space platform such as ISS and SSPS*". (JAXA). The mere fact that according to NASA the costs of a satellite can be kept down to 30-50% if a life extension service is used can push industries and governments to develop OSS technologies and revolutionize the space industry.

When we started this paper, our initial theory seemed difficult to support, but as we studied the issue of space debris under various scopes, trying to get through apparent blocking points, we managed to go beyond the problem, and develop a view that is as complete as the literature allow it to be. To achieve this work, we started from a technical problem, and put it under the lights of geo-politic, economic and legislative considerations to reach a solution. We studied various hypotheses, confronted the authors and tried to get the best out of it. This project taught us that cultivating interactions between the different fields of action of an enterprise allows us to exceed the limit of our subject in order to create an innovative solution. As Margaret Heffernan wrote:

"*For good ideas and true innovation, you need human interaction, conflict, argument, debate*".

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