ACTIVE DEBRIS REMOVAL:
FROM THE MAIN BARRIERS TO THE DEFINITION OF A BUSINESS MODEL

BAUDET Lucille (Student at TBS)

RUFFIOT Manon (Student at TBS)

February the 3rd, 2016

TBS M2 – Aerospace Management

Supervised by

VICTOR DOS SANTOS PAULINO (Teacher at TBS)

Toulouse Business School (2015-2016)

ACTIVE DEBRIS REMOVAL: FROM THE MAIN BARRIERS TO THE DEFINITION OF A BUSINESS MODEL

Executive summary

The space industry has been facing some evolutions over the years. During the Cold War, access to Outer space was a way for each nation to assert their power. After this period, space activities started to grow up, mainly for science purpose. The result is that for a long time, space industry has been considered as an industry reserved for space exploration. The creation of Space X, in 2002, has completely reconsidered the space market, with the apparition of low cost launchers. This new market has forced industries to adapt their business model to this growing competitive market. Along the increase of satellite launches that proved the important market development, a serious issue has risen over the years: the accumulation of orbital debris. An author called Kessler has submitted a scenario in which debris will interact with each other, creating a chain reaction. This scenario, known as "*The Kessler Syndrome*", would prevent future access of outer space for a long time. Some institutions and committees are trying to find solutions for future launches but some experts do not think it will be sufficient to overcome this situation. Space debris remediation measures came out from the assessment of this situation. Active Debris Removal appears to be a solution to remove debris and inactive satellite from space. But some barriers seem to prevent industries to be involved in this area, being reluctant to invest in these kinds of technologies. Firstly, an overview of the situation will give a better assessment of the space debris issues. A market needs to be created in order to apply active debris removal technologies. One solution could be defining a valuable business model for industries, to would give the added-value for ADR. But it seems that the business model is not based on the creation of profits, but rather on their long-term preservation.
Key Words: *space Debris, Kessler syndrome, Active Debris Removal, Space Debris remediation, market barriers, barriers to entry, business model.*

Résumé

L'industrie spatiale a été confrontée à de nombreuses évolutions au fil des années. Pendant la Guerre Froide, l'accès à l'espace était un moyen pour les nations d'affirmer leur puissance. Après cette période, l'activité spatiale a commencé à croître essentiellement dans un but scientifique. Pendant un long moment, l'industrie spatiale a donc été considérée comme une industrie réservée à l'exploration spatiale. La création de Space X, en 2002, a complètement remis en cause le marché de l'espace, avec l'apparition d'opérateur de lanceurs low-cost. Ce nouveau marché a obligé les différentes industries à adapter leur business model à ce marché à la compétitivité grandissante. Parallèlement à la hausse des lancements de satellite, prouvant le développement important du marché, une problématique majeure a émergé au fil des années : la prolifération des débris spatiaux. Un auteur nommé Kessler a proposé un scénario dans lequel les débris interagiraient entre eux, créant une réaction en chaîne. Dans ce scénario, connu sous le nom de « Syndrome de Kessler », les futurs accès à l'espace pourraient être compromis pendant une longue période. Certaines institutions et autres comités essaient de trouver des solutions pour que les lancements futurs ne participent pas à l'augmentation des débris, mais certains experts pensent que cela ne sera pas suffisant pour surmonter la situation. La « collecte » active des débris

(ADR) parait être la solution pour retirer les débris et les satellites inactifs de l'espace. Mais des barrières semblent empêcher les acteurs de l'industrie de s'engager dans ce domaine, à investir dans ce type de technologies. Tout d'abord, un état des lieux de la situation donnera une meilleure évaluation du problème des débris spatiaux. Un marché doit être créé de manière à appliquer les solutions technologiques de collecte active de débris. Une solution pourrait être de définir un business model profitable pour les acteurs du secteur, de manière à apporter de la valeur ajoutée à la collecte de débris. Cependant, il semblerait que le business model ne soit pas basé sur la création de profit, mais plutôt sur leur préservation à long terme.

Mots clefs : *débris spatiaux, syndrome de Kessler, « collecte » active des débris (ADR), space debris remediation, barrières de marché, barrières à l'entrée, business model.*

Table of Contents

1 Introduction

On 13 November 1986, the explosion of an Ariane-1 H-10 upper-stage booster in 818 kilometers altitude led to an estimated total of 488 traceable objects of space debris. 10 years later, the 24 July 1996, the first collision resulting from this explosion occurred, involving the French active satellite Cerise and a fragment from the Ariane Rocket. This event brought for the first time awareness about orbital debris and initiated the consideration of the problem. Another kind of event occurred in 1997 when a woman named Lottie Williams, was running in a Tulsa park one morning, and was suddenly hit on the shoulder by a six-inch piece of metallic material, that belonged to a Delta II rocket. These events show that space debris can be an issue for both space activities and human safety on Earth.

In 2013, *Gravity*, a movie from Alfonso Cuaron, described a scenario in which an ISS astronaut's mission turned into a drama because of debris. This movie has been an opportunity to bring back this controversy topic on the agenda. A need for cleaning up space raises in the mind of the space community. Mitigation measures have been implemented in order to find solutions for the future satellites, but debris need to be removed actively. This concept is known as Active Debris Removal (ADR), giving remediation solutions. ADR supposes to find technical solutions to remove inactive satellites from space. But this process is surrounded by several barriers, from political & legal to technical and economic. These barriers are preventing the creation of a market for ADR technologies, where industries feel reluctant to get involved. This paper will try to give an overview of the main issues that are surrounding an ADR service market. The purpose is also to discuss how these obstacles could be overcome. As space industry is now driven by the need to get competitive advantage, is it only these barriers that are preventing the implementation of a market?

After giving an overview of the current situation and the consequences of the space debris proliferation, we will analyze the main barriers and reasons why an active debris removal market is difficult to implement. Finally, we will discuss the different solutions to overcome these obstacles, and the need to define a valuable business model for the concerned industries.

.

2 SPACE DEBRIS DEFINITION[1]

The Inter-Agency Space Debris Coordination Committee (IADC) defined space debris as "*all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional*."

What they mean by Space debris (also known as orbital debris or space junk) is not only the inactive satellites that reached their end-of-life, but also:

- Upper stages of launchers (used to place satellites in orbit);
- Objects intentionally released during a mission, which are called operational debris. These operational debris can be:
  - casings needed to protect instruments during the launch phase
  - mounting systems for solar panels or antennas before their deployment in orbit
  - release mechanisms;
- Fragments coming from a collision between two satellites or two objects, or from space object accidentally or intentionally exploding;
- Propellant residues from solid propellant motors that are used to carry out orbit transfers
- Ageing of materials in space due to the extremely hostile environment

In their article called "*conceptualizing an economically, legally and politically viable active debris removal option*", Emanuelli et Al. have divided Space Debris in LEO into three categories in terms of size, potential risks and possibility of detection, according to the following:

Size	Potential Risk	Detection	Number	Mass Fraction
> 10 cm	Complete destruction	Tracked	21 000	>95 %
1 – 10 cm	Partial/ Total destruction	Partially Tracked	500 000	<5%
<10 cm	Damage, can be shielded	Not tracked, statically assessed	>100 million	

Figure 1: The classification of space debris

[1] A Report of the International Interdisciplinary : "*Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris Congress on Space Debris"*

3 Space Debris Mitigation & Remediation

Most of the space debris can be found in the LEO region as it is the most solicited orbit; where space human activity is the most active, mainly for Earth observation. The LEO orbit is situated between 600 and 1,500 kilometers while the GEO orbit is situated at 36,000 kilometers, and is mainly used for telecommunications satellites. When GEO satellites reach their end-of-life, they use the propellant left on-board to be transferred into a “graveyard orbit”, in order to not interfere with other active satellites. As the LEO orbit is more over-crowded than the GEO orbit, solutions need to be found to clean up this orbit in priority. Some recent collisions between satellites, and the regularly manoeuvers from the ISS to avoid debris make the space actors aware that the issue of Space debris can no longer be ignored. Regarding this situation, the Inter-Agency Space Debris Coordinating Committee (IADC) and the United Nations Committee on Peaceful Uses of Outer Space (UNCOPUOS) have adopted a series of guidelines that aim to reduce the proliferation of space debris. Among them, the Space debris mitigation guidelines have been endorsed by the UN COPUOS in 2007. These guidelines set up requirements for the future space missions in order to mitigate or reduce the creation of new space debris. The mitigation efforts suppose to:

- Design the future satellites and rocket stages in order to limit the debris release during the operational life
- Minimize potential breakups by cutting all form of power on-board at the end of the mission
- Integrate post mission disposal in order to deorbit the satellites after their end-of-life[2]

However, regarding the abundant debris population already present in LEO, a need for an active process to remove the existing orbital debris arises in the space community mindset. Indeed, some experts consider that mitigation efforts will be not enough to guarantee and protect the long-term running of space activities. In this way, the concept of space debris remediation came out from the urgent need to actively clean up the space junk.

[2] (Joyeeta Chatterjee, 2013, *Legal aspects of space debris remediation: active removal of debris and on-orbit satellite servicing*)

4 Active Debris Removal: an issue becoming critical stake

4.1 Overview of the current space debris environment

The history of space activity starts in 1957 with the launch of the Russian Satellite, Sputnik, in 1957. This first launch triggers the race for space, and from this date, more than 4800 launches have placed around 6000 satellites into orbit (Emanualli, Chow, Prasad, Federico and Loughman, 2013). There are currently thousands of these satellites still in operation today, rather some other remain inactive in orbit. The use of Space for human activities is not without consequences, and some events have contributed to remind us that Space is starting to be overcrowded.

According to Paul Kallender -Umezu in - *A Market for Cleaning Up Space Junk?-;* several incidents led to the proliferation of space debris since the beginning of space activities. Among them, in January 2007, Chinese decided to launch a ballistic missile at their Fengyun-1C weather satellite, causing the destruction of the satellite and causing the creation of 3,000 traceable debris and 150,000 particles larger than 1 cm, representing a danger for the 100 coming years. Another event occur in 2009, when the Iridium 33 satellite and the 16-year-old Russian Cosmos 2252 satellite enter in collision and produced 2,000 tracked and 100,000 untracked debris objects. If we combined the explosion of the Fengyun-1C satellite and the collision between the Iridium 33 and the Russian Cosmos 2252 satellite, the two events caused an increase of debris in LEO by 60%. All these collisions and incidents bring awareness to the nations about the proliferation of space debris, as it compromises the future use of the Outer Space.

The U.S Space Surveillance Network has tracked about 15,800 items in orbit. In addition, there are at least 600,000 untracked objects between one and ten centimeters and more than 100,000,000 untracked objects between 0.1 and one centimeter, which therefore represent the main part of space debris (Adilov, Alexander and Cunningham, *Earth Orbit Debris : an Economic Model, 2013*).

A growing population of space debris increases significantly the risk of collisions. The main danger is the velocity of debris, which is approximately 11,000 kilometers/h for objects in GEO and 35,000 km/h in LEO. Associating such velocities with the huge kinetic energies, even the smallest objects can cause catastrophic results. A small piece of debris can make serious damage on operational satellites, while debris of one-half millimeter in size can kill an astronaut protected only by a spacesuit (Lawrence D. Roberts, *Addressing the Problem of Orbital Space Debris: Combining International Regulatory and Liability Regimes*, 1992).

4.2 Consequences of the Space debris

The space debris phenomenon is becoming an important issue for space activities and several consequences are rising from this space junk.

4.2.1 The Kessler Syndrome

In 1978, Donald J. Kessler and Burt Cour-Palais published in the *Journal of Geophysical Research* a written work entitled *"Collision Frequency of Artificial Satellites: The Creation of a Debris Belt"*. In this paper, they explained that there is a hazarding interaction between space objects leading to this consequence: "*…the debris flux will increase exponentially with time, even though a zero net input may be maintained*". The idea raised the alarms in the scientific community as to a possible chain reaction among space debris.

Kessler continued to develop his thesis in *Collisional cascading: The limits of population growth in low earth orbit* (1991). He described a scenario in which the space debris volume in low-earth orbit reaches a "critical density". Past this threshold, the increase in collision between debris and orbital objects would create even more debris. If not dealt with, the space exploration and satellite mission or the simply access to Outer space could become impossible for a long time.

This was a theoretical projection, but quickly this idea spread entitled "*the Kessler Syndrome*". After a number of years, and regarding the recent multiplication of space debris, what new perspective could be brought to this scenario?

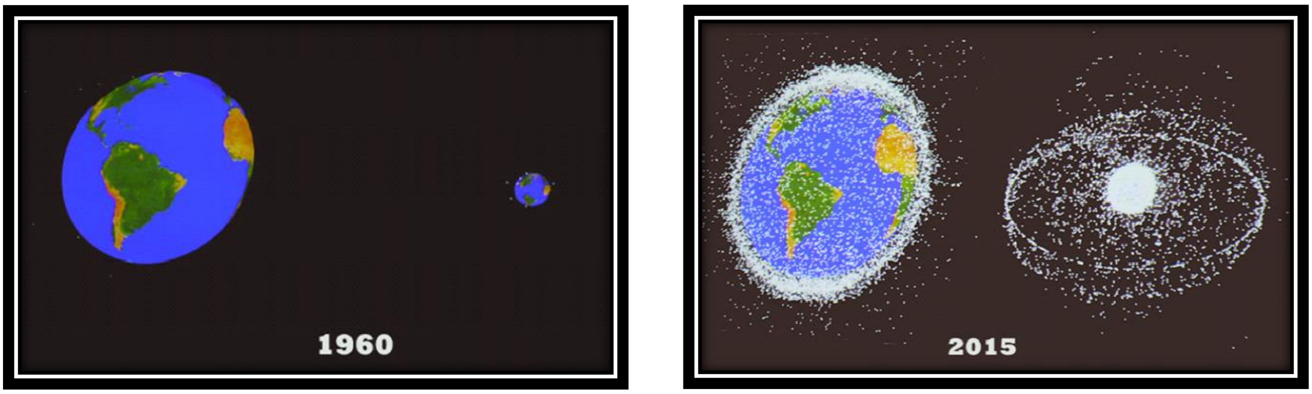


Figure 2: Visual representation of Space debris evolution since 1960 to 2015.

Is "*the Kessler syndrome*" an anxiety-provoking disaster scenario or a reality? Less than forty years later, Kessler gave his opinion on the issue. In September 2015, he explained to the "*Marketplace*" (American newspaper) that we actually reached the critical density aforementioned. The consequence: from now onwards, the interaction between all the debris already present in space is creating more debris than we can remove, even if the launches are stopped.

4.2.2 Why is it essential to remove space debris?

The consequences of the large amount of debris are numerous. According to Emanuelli et Al., space debris is currently a problem for both operational satellite and humans aboard the International Space Station. Orbital debris is a threat for the future human activities and presence in space, but also for human safety on Earth. Indeed, inactive satellites as well as all orbital debris present in the LEO region can be naturally attracted by the Earth and probably endangering human lives by re-entering the Earth atmosphere. Most of these objects will be totally disintegrated, although it has already happened in the past that objects did not totally burn in the atmosphere (example of Lottie Williams explained in the introduction). In addition to these consequences, space debris can also led to economic loss results.

There are three major types of economic threats:

- An effective collision between two satellites or a satellite and a piece of debris can cause serious damage an operational satellite, able to end the mission. In 2013, Pegaso, an equatorial satellite hit a former Russian rocket debris only one month after being placed into orbit. After this collision, the satellite became inactive. The manufacturer and the government respectively lost 80k€ and 700k€.[3]

- To avoid this type of disaster, space agencies are obligated to practice "avoidance maneuvers". The International Space Station (ISS) performed 18 avoidance maneuvers since 1999 (S.Michel, *Les débris spatiaux*, CNES). These maneuvers require a need for tracking and registering all the debris in catalogs, and such measures need economic and technological resources. In France, the CNES is constantly monitoring its fleet of 18 satellites to arbitrate if avoidance maneuvers are necessary or not. Against small debris impact, satellites can reinforce the protection of their structure, but their masses (and consequently launch costs) might increase.

- Space business is also threatened by the proliferation of space debris. Even if the risk of collision is about 1/1000, the latest collisions show that this type of event can represent significant loss for the owner of the satellite, losing both the mission cost and its revenue. If there is no action to improve the situation, what Kessler explained in his recent words in Sept 2015, the risk is that space missions will be difficulty allowed and the revenue generated from these space activities would be lost.

In 2008, the global revenues for satellite were $144 billion including $84 billion just for satellite services. It is a 14.2 % annual average increase from 2003-2008[4] according to E. Dunstan, B.Werb (2009). These figures show that the market is growing exponentially. The development of space exploration as well as the value generated by space missions and entrepreneurship around satellite usage will require finding solutions to protect the use of Outer space.

4.3 A need to react: Space debris remediation

[3]Le monde.fr : « *Collision entre l'unique satellite équatorien et les débris d'une fusée russe* » (2013)
[4] E. Dunstan; Werb (2009) Legal and Economic Implications of Orbital Debris Removal: A Free Market Approach; International Conference on Orbital Debris Removal December 8-10, 2009 Reston, VA.

Regarding these consequences, solutions have to be considered in order to protect the long-term use of the outer space. The purpose of mitigation measures proposed by IADC is to reduce the growth, but the long-term proliferation of space debris is still expected, even with full compliance, and even if all launch activities is stopped. As mentioned earlier, some experts even think that the Kessler syndrome has already started.

Recent studies[5] have indicated that mitigation measures will be not enough to ensure humanity's access to space and protect the long-term space activities (Emanuelli, Chow, Prasad, Federico and Loughman, 2013). This is the reason why the concept of Active Debris Removal appears, in order to remove inactive satellite that present a high risk of collision. While this concept is not new, it has not yet been implemented by anyone. Indeed, the concept of ADR is surrounded by several barriers, from technical to economic; as such systems require huge development cost. ADR is also subjected to regulatory constraints because of the dual use nature of these technologies, but also to the political issues associated.

5 The barriers preventing the creation of an ADR market

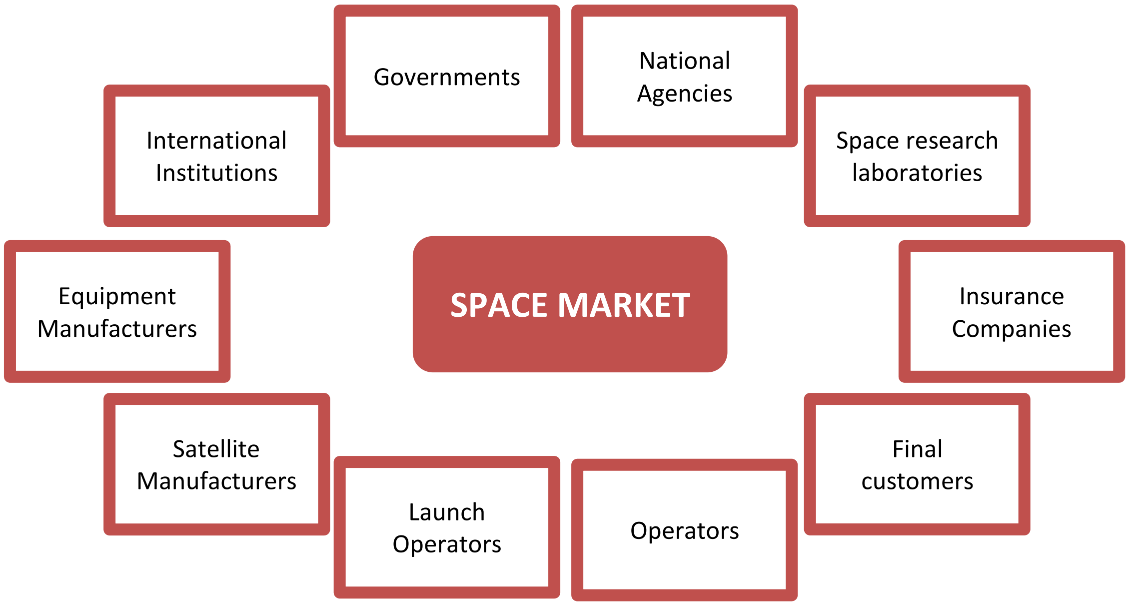
Regarding this situation analysis, it seems obvious that removing space debris is necessary and vital for the protection of space as well as for the space industry balance. The Active Debris Removal technologies are surrounded by several barriers that prevent their implementation. Before analyzing the main obstacles, this is important to get an overview of the space market, to understand who need to cope with these barriers, and how some actors could act to resolve them.

5.1 Who is affected by these barriers? The Value chain of Space market

The organization of Space Industry is built between actors at different level, concerned by different goals, means and stakes. Before wondering how they can act in the Space debris removal, it is necessary to understand how they interact together.

[5] J.-C Liou, "*An Assessment of the Current LEO Debris Environment and the Need for Active Debris Removal*," in ISTC Space Debris Mitigation Workshop, Moscow, 2010.

5.1.1 Value Chain of the Space Industry:



If we break down the Space Market according to the Porter Value Chain, there are *the Primary activities*:

- **Satellite manufacturers**: All the companies which are manufacturing the end products. The market is very concentrated. The main companies are Loral, Boeing and Lockheed-Martin for the United States and Airbus Defence & Space and Thales Alenia Space for Europe. Recently, some new actors emerged: Space X for instance with its low cost satellites program, or Google and Amazon who have planned to develop their own satellites, transforming the market configuration and competition.
- **Equipment manufacturers**: They provide major subsystems, systems and components for the satellite manufacturers.
- **Launch operators**: They are mainly state or government financed. American launchers are completely dedicated to governmental and military launch missions.

and *the Support activities*:

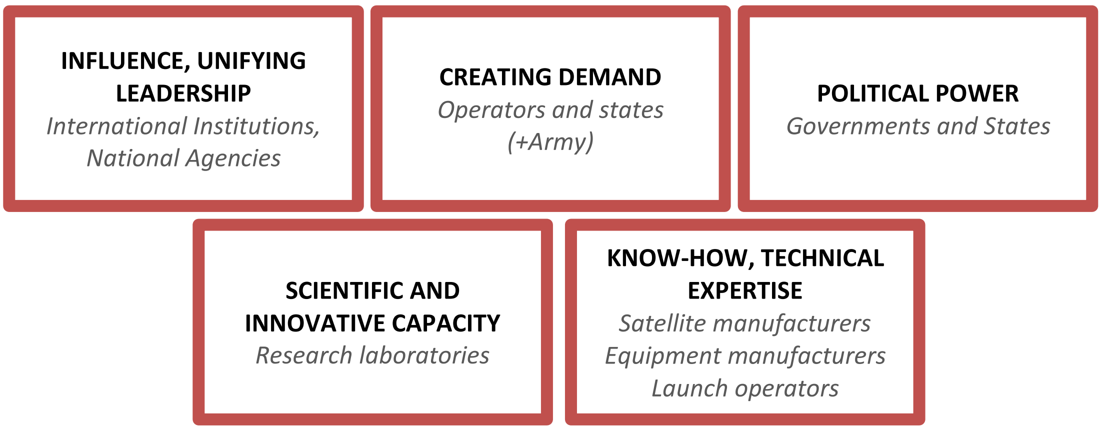
- **International institutions**: The NASA (United States) or ESA (Europe). They are the two most important institutions about space after the slowing down of the Russian Space Agency, since the end of the Cold War.
- **National agencies**: In a lot of countries, there are public agencies which take a great part in space activity, in multiples areas: economic, politic and scientific (e.g. CNES in France)
- **State and governments**: They are, in most cases, at the same time investors and customers of the satellites' manufacturers. The Army also plays a crucial part in the satellite marketplace. Governments represent 30% of the civil satellites and 25% of the military ones.

- **Operators and final customers:** The operators are the one using the satellite for economic purpose. They represent 40% of all the satellites in orbit. Iridium Satellite, EutelStat or Global Star are ones of the most important.
- **Research laboratories**: They are promoting the scientific innovation in the space market.
- **Insurance companies**: Because there are huge risks on satellite missions, mostly during the launch phase (10% of fail), the insurance companies are compulsory. According to the *March, 29th of 1972 Convention* about *International liability for damages caused by space object*, it is the launch operators who are supporting all risks and liabilities during the launch phase and the first operations on orbit. After, this is the satellite owner or operator during 1 year.

Fundamental interactions exist between National Space Agencies and governments. According to Henri Revol in his Rapport n°293 (2001) « *La politique spatiale française: bilan et perspectives* », space agencies hold the technical and scientific competencies and the long-term vision while Governments have the politic power and financial means. Then, space agencies can influence governmental programs and states bring funds. The interaction between space agencies and research laboratories make possible the transition of a scientific idea or discover to a more structured project, the passage of a scientific proposition to a program. Space agencies support the R&T activities in helping research laboratory jointly with the government.

Finally, the space market is regulated by the space law, that have been implemented by national committees like IADC (Inter-Agency Space Debris Coordination Committee) gathering the main National Space Agencies and UN COPUOS (United Nations Committee on the Peaceful Uses of Outer Space) including states, international organizations and both intergovernmental and non-governmental organizations

5.1.2 Synthesis of the space actor implication



This value chain analysis was necessary to understand how space actors are linked and how they are implicated in the space market. According to this analysis, both equipment manufacturers and satellites' manufacturers are the ones who can be involved in the ADR market, through the proposition of technical solutions (with the support of national space agencies). International Institutions and governments are the ones who could provide support to promote the creation of an ADR market, though the resolution of the main barriers.

5.2 The legal & political barriers

Some barriers seem to prevent industries to enter the market of space debris remediation. The creation of a market for Active Debris removal is compromised by several factors preventing space industries from being involved in this new area. According to Blees et Al. in their research report called "*Barriers to Entry Differences in barriers to entry for SMEs and large enterprises*" (2003), firms will enter the market only if the profit will give them a long-run competitive level. But several mechanisms can prevent firms from entering the market. There can be barriers to their entry that do not go along with the industry benefits. One of the main barriers preventing the creation of an ADR market is the legal & political framework.

The international aspect and utilization of the Outer space require all nations to become more aware of the problem. The proliferation of space debris needs to be controlled through worldwide coordination and common agreement, using common mitigation and remediation solutions.

Historically, space law has been created and based on three conferences on the Exploration and Peaceful Uses of Outer Space, which took place in 1968, 1982 and 1989. These conferences, called UNISPACE, were meant to engage states on international cooperation about the peaceful uses of space but also to promote a global dialogue on key issues related to space exploration and exploitation. [6]

Space Law includes five major treaties; two of them are addressing the Active Debris Removal issues:

- The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space - the Outer Space Treaty (OST) of 1967
- The Convention on International Liability for Damage Caused by Space Objects of 1973 (the Liability Convention), defining the liable party as the "Launching State".

Paul Kallender-Umezu, in its article called - *a market for cleaning up space junk?* - analyzed the main weaknesses of these two treaties. According to him, one of the main issues is that there is no clear definition of space debris; nor any binding legal definition of them. But the most important problem is that there are no regulations mentioning who have to remove debris. Indeed, there is no legal document or treaties that clearly explain who must remove their satellites, or their fragments, and the space law did not mention any obligation to do so. The debris and fragments are considered as individual objects. Then, in the case of an active debris removal process, these two treaties (the Liability Convention & the OST) do not tell who is responsible if a third party removes a piece of debris by mistake, or cause trouble to a piece of debris which can damage another satellite.

[6] http://www.unoosa.org/oosa/en/aboutus/history/unispace.html

Also, any U.S components or technologies onboard a spacecraft is covered by *the U.S. International Traffic in Arms Regulations (ITAR),* with a need for specific export authorization. ADR may be subjected to this procedure as they might use U.S. components, and they would require the ITAR-free classification. In addition, in the Space & Defence industry, every object or component which may perform an “atmospheric re-entry” maneuver is considered as a weapon and should have a specific classification. As ADR is used to remove objects that will probably be disintegrated in the atmosphere, such a system must have a specific legal classification to get the right for being launched.

From a political point of view, some satellites have been launched for military or security purposes; this is the reason why some states like U.S, Russia or China are reluctant to allow other governments to interfere with their satellites or fragments. In this frame, the space law does not mention who has the right to remove debris. The dual-use nature of ADR technologies supposes significant strategic and military implications which require political considerations.

According to a Report of the International Interdisciplinary Congress on Space Debris, there is clearly a lack of legal and political regulations concerning Active Debris Removal technologies and solutions. To face these main issues, regulatory efforts to reduce the proliferation of orbital debris have been realized in the form of international non-binding guidelines (such as the IADC and UN COPUOS Guidelines, mentioned before) or national regulations and procedural rules (such as NASA’s Procedural Requirements for Limiting Orbital Debris).

Space actors try to make efforts through the implementation of national and international debris mitigation measures. In 2002, five European space agencies (ASI, BNSC, CNES, DLR and ESA) issued the European Space Debris Safety and Mitigation Standard, which became in 2004 the European Code of Conduct on Space Debris. In addition, the CNES prepared in 2009 the Technical Regulations which are now applicable through the French Space Operations Act (French Space Law). This law is applicable since December 2010 and will be fully applicable in 2021. During this period, some obligations are currently transitory measures based on a “best effort” principle to allow the space industries to adapt themselves. The European Space Agency also launched the “*CleanSpace*” initiative aiming to increase attention to the environmental impacts of its activities, both on Earth and in space, and encouraged industries to take measures to reduce these impacts.

Internationally, the U.S. National Space Policy of 2010 reiterated the American policy to minimize space debris and preserve the space environment for the responsible, peaceful, and safe use of all users. In 2006, China released a white paper entitled “China’s Space Activities in 2006,” including an active participation in debris mitigation mechanisms and policy efforts at the international level. In 2010, China finalised national regulations implementing space debris mitigation measures similar to UN COPUOS and IADC Guidelines (*Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris,* A Report of the International Interdisciplinary Congress on Space Debris, 2011)

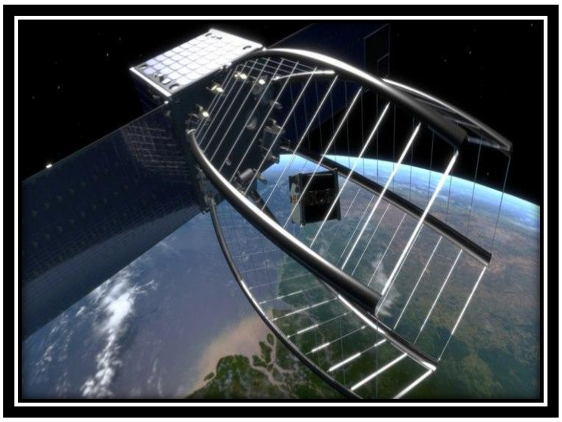
All this involvement coming from the different nations is showing the shared awareness about space debris issue. The problem is these efforts only lay down in non-binding guidelines, without addressing any legal or political framework that would obliged space industries to take measures. Indeed, there is neither legal obligation, nor penalties for those who do not respect these guidelines. Therefore, the requirements are hardly followed by the space manufacturers. As an example, and according to C. Bonnal from CNES: "*only 50% of the launched satellites today are compliant with the French Space Law".*

5.3 The technical & economic barriers

In addition to the political & legal framework that needs to be consolidated, there are also some technical & economic barriers that prevent the creation of an ADR service market. Some of the space actors have been considering and proposing some solutions, but they remain as concepts.

A wide range of technologies are currently under studies, among them:

- **Capture systems : using throw-nets, harpoons, robotic arms:**
  - **Throw-nets:** The Swiss research institute EPFL is building a spacecraft that could grab orbital debris and then carry it back towards Earth. This technology will be based on a folding conical net to capture bits of space garbage.[7]
  - **Harpoons:** Harpoon concept for capturing space debris has already achieved some maturity development at Astrium Stevenage. [8]
  - **Robotic arms:** The robot arm captures and stabilizes the target, visualize the final docking with its own camera, attaches the de-orbit devices, and supports the resupply process. DLR's Institute of Robotics and Mechatronics has developed a state-of-the-art lightweight robotic arm, derived from the space qualified ROKVISS technology, in use on the ISS.[9]



Active De-orbiting of debris requires some functions like mechanical interfacing but also rendezvous maneuvers that are the most complex phase. (C.Bonnal, *Active Debris Removal: current status of activities in CNES,* 2013)

Figure 3: Swiss Cleanspace One Spacecraft

[7] http://www.gizmag.com/cleanspace-one-orbital-debris-satellite/38348/
[8] Wormnes et Al., ESA technologies for space debris remediation
[9] Loesch, M., Bruin, F. De, Castronuovo, M., Covello, F., Geary, J., Hyde, S., Aachen, R. (2010), "*Economic Approach for Active Space Debris Removal Services"*

Most of these debris removal concepts rely on one or more systems that are unproven technology (Johnson, 2007). In space activities, Technology Readiness Level (TRL) is used to assess the maturity of evolving technologies (devices, materials, components etc.). A new technology is not suitable for immediate application. Indeed, the system/technology is subjected to experimentation, maturation and realistic testing of the concept before getting the qualification and authorization to go in space (Emanuelli et Al. 2013). This TRL procedure can be long (scale going from 1 to 9), and development costs are very high in order to reach the TRL 9.

As the concept of ADR has not been demonstrated in orbit yet, the TRL is still low, and high non-recurring costs need to be taken into consideration. According to the definition of Lisa Guerra from NASA: "*Non-recurring costs include all costs associated with the design, development and qualification of a single system. Non-recurring costs include the breadboard article, engineering model, qualification unit and multi-subsystem wraps*". Then, once the first debris removal system would have been in space to prove the concept feasibility, the follow-on mission will only support the recurring costs, which represent the costs associated with the production in serial of the approved system (Lisa Guerra, 2008).

The implementation of an ADR system includes these non-recurring costs related to the development of the technology maturation, but also includes the mission cost. As an example, SSTL (a satellites' manufacturer) has estimated the costs model to remove Envisat with the chaser concept. The prices reach around €65M per debris removed with a chaser, and €30M per debris removed via a Shuttle. To these removal costs, €135M need to be added to finance the initial spacecraft manufacturing to launch the system, and the price of the launch itself (SSTL, 2013).

Therefore, development costs are too high to be supported by equipment or satellites' manufacturers themselves. If technical barriers can be easily overcome, economic barriers will required the financial support of institutions to make industries involve in this market.

Reminding Kessler's words : «*We're at what we call a 'critical density' — where there are enough large objects in space that they will collide with one another and create small debris faster than it can be removed*". The Kessler syndrome is threatening the future launches and space missions. They are therefore many reasons for addressing the issue of ADR and try to find solutions to the main barriers explained. Is it that difficult to overcome these barriers? Is it only these barriers that prevent industries from being involved?

The precautionary principle should be applied to space environment, as we did with the environmental cause on Earth. This precaution could save an expanding industry which generates a lot of economic value. The preservation of the profits is what could give value to a potential business model.

6 Are these barriers impossible to overcome?

Lowering these barriers or preventing their creation is therefore a key element for the setting up of an ADR market. These barriers can be various, relating to cost advantages, capital requirements, and government policies. In the case of Active Debris Removal, we identified several barriers, political & legal as well as technical & economic. To stimulate the creation of the market, the efforts should be stressed on lowering in a first place the political & legal barriers.

6.1 A primordial condition: establishing a strict legal framework

First of all, a legal framework has to be implemented. There are too many unclear aspects in the Space law, and even more about Space Debris. L.Pereira-Baia, in "*Le cadre juridique international des activités spatiales : l'exemple des telecommunications par satellites"* (2000-2001) wrote that "*as the sea, rivers and the air, the extra-atmospheric space is a fully-fledged space and cannot be ignored by the law [it] doubly interests Humankind as an "passive" space in which one individuals can move and as an "active space" from which one activities are carried out for a better understanding of the mankind and of its environment*."

As a reminder, the main issues about space debris legislation are:

- An unclear definition of space debris
- An uncertainty on property and responsibility
- The dual use of ADR solutions
- Recommendations based on non-binding guidelines

Firstly, involvement must be shared among nations, and the international community needs to create mechanisms to facilitate the rules and definitions. These rules include both the jurisdiction and control issue regarding ADR as well as the authorization for cleaning up space with such kind of technologies. A proper and legal framework should be also clearly defined in order to protect the parties involved according to P.Kallender-Umezu (2011) in *"A Market for Cleaning Up Space Junk?"*.

There is a need for a legal definition of non-functional space debris as separate from functional spacecraft. Indeed, K-H.Bockstiegel, M.Benko and S.Hobe in *Space law, Basic legal documents, v1* (2005) explain that for instance United States make a difference between "orbital" debris those resulting only from mankind industrial activity and "space" debris which is a larger definition as it includes also the meteorite. The international community has to agree on one clear space debris definition.

Once the definition is properly set up, other solutions can be implemented. To establish an effective legal & political framework related to ADR service market, there needs to be[10]

- International agreement and transparency on which objects are selected for removal, and who should remove debris
- The clarification of the liability regime :
    - Identification of the proportion of debris for which each State is responsible[11]
    - Development of protocols/agreements between Launching State and third party removal entities
    - Defining who is responsible if a 3rd party is damaged during the removal process
- International agreement on the implementation of Active Debris Removal activities, with binding rules and regulations
- The creation of an Intergovernmental Organization (IGO) that will coordinate ADR missions[12]

The creation of an Intergovernmental Organization (IGO) that will coordinate ADR missions is an essential point to achieve those different goals. The IGO would coordinate mitigation and remediation activities and ultimately contract for ADR missions (SSTL, 2013). The organization could be a way to resolve the main obstacles from the political & legal framework. But this organization must have the power to legislate; to implement binding rules and regulations. Only guidelines and recommendations will be not enough.

6.2 Overcoming the economic barriers

3.2.1. From economic barriers to the definition of a business model

The creation and definition of a market for ADR cannot be achieved without finding solutions to the main obstacles. We saw that the priority relies on a political & legal framework that would resolve the main issues. But reducing these barriers will not

[10] B.Weeden, "*Overview of the Legal and Policy Challenges with Orbital Debris Removal*" 61st International Astronautical Congress, Prague, 2010
[11] Michael W. Taylor, "Orbital Debris: Technical and Legal Issues and Solutions" (L.L.M. thesis, McGill University, 2006)
[12] SSTL (2013); "*Service oriented approach to the procurement/development of an active debris removal mission*"

be sufficient for the creation of an ADR service market. There needs to be industries involved in this new market, and interests might be given through the definition of a valuable business model that could provide commercial benefits.

For David J. Teece in his article *Business Models, Business Strategy and Innovation, "A business model articulates the logic and provides data and other evidence that demonstrates how a business creates and delivers value to customers. It also outlines the architecture of revenues, costs, and profits associated with the business enterprise delivering that value".* Regarding this definition, the basis of a business model is to explain how the companies deliver value to their customers and how this value will be converted into profits for the customers who will pay for it. Active debris removal activities do not provide this added-value in terms of commercial business, neither for satellites manufacturers nor for the launcher operators. This is therefore difficult to identify the relationship between debris removal and individual commercial interests (Loesch et Al., 2010). According to David J. Teece, "*every new product development effort should be coupled with the development of a business model which defines its 'go to market' and 'capturing value' strategies*". For him, technological innovation will not automatically guarantee commercial success. With regards to these arguments, the only way to create a market for ADR is to create the added-value for the customer and define the revenues model.

In order to define the mechanisms to capture value from ADR, this is important to clearly identify firstly the addressable market. The market for ADR concerns the orbital objects to remove in priority, and the European Space Agency has defined 3 criteria to select them:

- **The mass**: the target must have a high mass, as they have the largest impact in case of collision
- **The collision probability**: the selected objects should have high collision probability (greater risk of generating new debris)
- **High altitude :** when the object is in high altitude, the orbital lifetime is longer[13]

ESA, as a European institution but also all institutions from the public sector, must stimulate and initiate activities according to this target market. As Brian Weeden says: "*There needs to be an international demonstration mission for active debris removal" (*"*Overview of the Legal and Policy Challenges with Orbital Debris Removal,* 2010). Institutions should support the removal of space debris financially, to encourage the creation of an ADR service market from the demand side. This idea is also supported by Emanuelli et al. reckoning that this demonstration mission could convince stakeholders to be involved in this new service market. Indeed, this could help overcoming some of the technical issues, give a better assessment of the mission cost, and resolve operational issues. The first mission, funded by institutions, would prove the feasibility of the concept, but also give the framework for future application mission. The institutions would cover and assume the technology development costs, which mean financing the non-recurring costs related to the first mission. The equipment's manufacturers would only have to support the recurring costs for the follow-on mission.

3.2.2 A "non-classical" business model

[13] http://www.esa.int/Our_Activities/Operations/Space_Debris/Debris_removal

Defining a valuable business model seems to be required to convince space actors to go in the market, as it defines the revenue model provided by the activity. According to J-C. Liou in his presentation "*Challenges and Opportunities for Orbital Debris Environment Remediation"*, the removal of 5 debris per year would be enough to stabilize the LEO environment. As the collision probability is currently 0,3% for the LEO satellites, this "*five objects per year*" rule would decrease this collision rate. Decreasing the collision probability means also decreasing the risk to lose both the satellite cost and the mission revenues, which can represent billion of euros.[14] Therefore, the revenue model given by the active debris removal technologies are not based on a classical business model that delivers profits to the customers, but through a probability of saving the current profits. Indeed, the value of ADR is mainly given on preserving the long-term space activities, and not necessarily on giving direct profits to the ADR manufacturers.

The ADR service market is therefore reconsidering the classical business model, without meaning that it cannot be valuable. The main challenge today is to convince industries that a relevant business model exists through the ADR technologies, and that the cost of doing nothing could be worse than trying to implement solutions from now on[15]. This is what can give value to the ADR service market.

6.3 The coercive manner: financing through taxes

Another way to give value to an ADR business model is to provide the revenue mechanism. The revenue model could be given through some funds that would be coming from taxes. As mentioned, the preservation of the profits represents the added-value for an ADR business model. This preservation supposes to deal with the space debris issues as with the environmental cause on Earth. From this assessment, the "who" should pay and "how" need to be defined.

One of the ideas to finance ADR solutions is to impose fees on satellite launches. M.Ansdell explained in *Active Space Debris Removal: needs, implications, and recommendations for todays' geopolitical environment* that the amount could be calculated according to the calculation of the "debris potential of the mission". Not only launch operator should pay this tax, but also the satellite manufacturers, the service provider and the originator of the mission. For the calculation of tax value, M.Emanuelli et al. explain that to fix the value, the stakeholders have to provide the measurement of the activity value. According to them, "*this value proposition determination must take into consideration collisional risk due to debris and its potential growth (both catastrophic risk and simply mission-limiting risk). In addition, it needs to consider the time-discounted value of the space assets at risk (both present and future assets), and finally the cost of reducing that risk at different points*". To resume, a calculation

[14] From C.Bonnal Explanations and ideas
[15] The assessment of this value is under studies by members of the Chaire Sirius (Toulouse Business School)

between risk and added value has to be done by the whole chain value of space industry in order to estimate the amount.

This solution is based on the Pigou externality analysis in *The Economics of Welfare* (1920). He was one of the first to establish the idea of the "polluter pays" principle to solve the problem of reducing pollution. In the case of space debris, the variable "pollution" can be assimilated to the debris, but there are not directly "released" during the production of the satellite or its functioning. This pollution released occurs when the satellite is no longer in service. So it seems to be fair to estimate a potential of debris before the launch. If all the actors of the satellite conception and production are included in the payment of these fees, it prevents one of the parties to reverberate the costs increase on the other.

If the tax is calculated on the forecasted potential of debris releasing of the satellite, this solution is more a "laissez-passer" than non-compliance. This solution could turn on tradeable emissions permits, like the carbon tax did, so to avoid speculation risks on this type of funding, the implementation has to be very strict and precise. But the risk is way lower because of the concentration of the market.

J. Dunstan and B.Werb, from the Space Frontier Foundation, during the International Conference on Orbital Debris Removal (2009) detailed a scenario to create a fund for debris removal on their presentation *Legal and Economic Implications of Orbital Debris Removal: A Free Market Approach*[16]. They named it "Orbital Debris Removal and Recycling Fund" (ODRRF).

Firstly, satellite operators and launching states are contributing to the ODRRF, based on "threat criteria of new launches". Those criteria are evaluated per the ODRRF who have beforehand analyzed the value of Space Debris. The ODRRF also assists companies with re-registration and oversee removal actions to guarantee payment to private companies. The private companies are the entities proceeding to the removal. They rank in order of importance the debris and re-register them for liability purpose. After the removal, those companies receive payment from the ODRRF. Insurance companies have also interaction with ODRRF and companies: removal companies acquire insurance and ODRRF monitor with the insurance industry. This concept will allow a virtuous circle and the value would be created by removing debris.

For M. Loesch, F. de Bruin, M. Castronuovo, F. Covello, J. Geary, S. Hyde and W. Jung in *Economic Approach for Active Space Debris Removal Services* (2010), it is governments and organizations that must reach an agreement and manage the fund for active debris removal.

Overall, the different systems to fund through taxes rely on launch fees. Solutions involve commercial companies to remove targeted debris, and those companies are directly or indirectly paid by the taxes. This system may initiate the creation of an ADR market by developing competition between private companies and commercial stimulation for innovation and technologies growth.

[16] See all the presentation : https://spacefrontier.org/wp-content/uploads/2009/12/Legal-and-Economic-Implications-of-Orbital-Debris-Removal-A-Free-Market-Approach.pdf

7 Conclusion

Is the Kessler syndrome becoming a reality? This is a question the space community has to answer today, dealing with the consequences of human exploration. The space community is currently showing its interests to solve the situation through the implementation of measures, but these only concern future launches. Active Debris Removal has been created as an additional solution, in order to actively clean up the Outer space, and protects any long-term activities. The ADR service market is difficult to implement, as it is surrounded by several barriers, which are preventing the development of an ADR market.

However, after identifying them, we could see that solutions can be implementing and that it is essential to treat them in a logical order. Firstly, the implementation of a strict legal framework at the international level will allow a global consensus and the union of resources and ideas. Removing grey areas on jurisdictions and giving the power to an international organism will allow the development of a concrete ADR program. An ADR program would help the implementation of effective solutions, creating a legal structure that will lead to an enabling environment.

Once this environment is implemented, a business model for ADR can be thought and realized in good conditions. Indeed, the main obstacle is to define a valuable business model, as it is not based on the creation of profits. The creation of such a market should be initiated by institutions (like ESA) who have the means to be the first to launch ADR solutions. A demonstration mission would overcome the problem of high development costs which make space actors reluctant to get involved. A valuable business model needs to be defined to stimulate the interests of space industries, but it seems that the value of ADR is given by the preservation of space activities profits, rather on their creation.

This “non-classical” business model must be joined by a tax system that would have the two-fold impact on concerned actors, involving them contractually and financing effective implementation of ADR solutions. This third step would enable the creation of an ADR environment and stimulate commercial interests. The challenge today is to convince the stakeholders of this model.

References

- A Report of the International Interdisciplinary : "*Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris Congress on Space Debris"* Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee Forty-eighth session Vienna, 7-18 February 2011 Item 7 of the draft provisional agenda* Space debris

- Adilov, N., Cunningham, B. M., States, U., & Academy, N. (n.d.). (2013) *Earth Orbit Debris: Economic Model.*

- M.Ansdell *"Active Space Debris Removal: needs, implications, and recommendations for todays' geopolitical environment"*

- K-H.Bockstiegel, M.Benko and S.Hobe (2005) *Space law, Basic legal documents, v1*

- M. Emanuelli, G. Federico, J. Loughman, D. Prasad, T. Chow (2013) *"Conceptualizing an economically, legally, and politically viable active debris removal option"*64th International Astronautical Congress, Beijing, China.

- E. Dunstan; Werb (2009) *Legal and Economic Implications of Orbital Debris Removal: A Free Market Approach*; International Conference on Orbital Debris Removal December 8-10, 2009 Reston, VA

- Lisa Guerra (2008) "*Cost Estimating Module*" Space Systems Engineering, version 1.0

- Johnson (2007), "*Debris Removal: An apportunity for Cooperative Research?* Space Situational Awareness Conference 25-26 October 2007

- Kallender-umezu, P. (2011). G-SEC WORKING PAPER No. 30 *"A Market for Cleaning Up Space Junk?*"

- DJ.Kessler (1991) "*Collisional cascading: The limits of population growth in low earth orbit"*

- DJ.Kessler, B.Cour-Palais (1978) *"Collision Frequency of Artificial Satellites: The Creation of a Debris Belt"* Journal of Geophysical Research.

- ESA website, available at:
- http://www.esa.int/Our_Activities/Operations/Space_Debris/Debris_removal

- J.-C Liou, "*An Assessment of the Current LEO Debris Environment and the Need for Active Debris Removal*," in ISTC Space Debris Mitigation Workshop, Moscow, 2010.

- J.-C. Liou, PhD, "*Challenges and Opportunities for Orbital Debris Environment* Remediation", 2nd European Workshop on Active Debris Removal CNES HQ, Paris, France, 18-19 June 2012

- Loesch, M., Bruin, F. De, Castronuovo, M., Covello, F., Geary, J., Hyde, S., Aachen, R. (2010). *Economic Approach for Active Space Debris Removal Services*

- *March, 29th of 1972 Convention* about *International liability for damages caused by space object.*

- L.Pereira-Baia (2000-2001) *« Le cadre juridique international des activités spatiales : l'exemple des telecommunications par satellites »*

- A.Pigou (1920) "*The Economics of Welfare"*

- H.Revol (2001) *"La politique spatiale française: bilan et perspectives"* Rapport n°293.

- Leonard Vance & Allan Mense, "*Value analysis for orbital debris removal*", Advances in Space Research 52 (2013) 685–695

- S.Michel (2014) "*Les debris Spatiaux"* CNES.

- Lawrence D. Roberts (1992): *Addressing the Problem of Orbital Space Debris: Combining International Regulatory and Liability Regimes*

- SSTL (2013); "*Service oriented approach to the procurement/development of an active debris removal mission*"

- Michael W. Taylor, "*Orbital Debris: Technical and Legal Issues and Solutions*" (L.L.M. thesis, McGill University, 2006)

- David J. Teece (2009), "*Business Models, Business Strategy and Innovation"*

- B.Weeden, "*Overview of the Legal and Policy Challenges with Orbital Debris Removal"* 61st International Astronautical Congress, Prague, 2010

- K. Wormnes, R. Le Letty, L. Summerer, R. Schonenborg, O. Dubois-Matra, E. Luraschi, A.Cropp, H. Krag, and J. Delaval, *ESA technologies for space debris remediation*

8 Acknowledgments

We would like to thank Victor Dos Santos Paulino for supervising our work and giving good advices for the elaboration of this paper.

We would like to thank also Aurélien Pisseloup from Airbus Defence & Space, who gave us an overview of the main issues and solutions for Active Debris Removal, which contributed to the content of this paper.

Finally, many thanks to Christophe Bonnal from CNES, who always took the time to answer our questions and give us very good explanations and ideas concerning this topic.