IS SPACE MARKET READY FOR LEO DEORBITING COMMERCIAL SERVICES?

By

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Contents

Executive Summary

Commercial deorbiting service of end-of-life satellites in LEO is not a new topic. But some key figures are still missing according to the former researches. This research presents a new approach to analyze the market potential, mainly from an innovation project's perspective.

In this research, a series of management tools, are implemented to get a structured process and sound results. PESTEL, Demand Readiness Level, Technology Readiness Level and Bibliometrics, are selected due to their strong relationship with innovation projects.

To get a better understanding and to make a better analysis of the topic, the primary sources and secondary sources are efficiently utilized in the research. 11 interviews from all the related aspects and 38 academic articles, supplemented by websites and other resources, are the main sources for different part.

Following the "Funnel approach", the market potential is analyzed by narrowing down the scope step by step, combining a forecast analysis. From the global analysis of all the satellites on orbit to the non-military LEO satellites, the end-of-life (EOL) satellites are discussed step by step. The result of the analysis shows the high market potential of commercial deorbiting services.

To better understand the participants and draw the direction of identifying potential customers, stakeholders in commercial deorbiting services are analyzed. A series of stakeholders, including governments and political regulators, satellites owners and manufacturers are identified and discussed. Their positions, interests and power are discussed. A PESTEL analysis for all those stakeholders follows. A snapshot of the influence from all the PESTEL factors is captured. The analysis demonstrates that the willingness to pay for this service and to transform the concept into a beneficial business model seems to be dampened by a wait-and-see approach.

Based on the stakeholder analysis and PESTEL, eight potential customers with the DRL from 0 to 7 are identified. The potential drivers to mature them are mainly discussed in the section. The current DRLs and probabilities of potential drivers show that government space agencies (e.g. ESA) and mass constellation owners have the highest possibility to be a customer of commercial deorbiting service. The further discussion shows that government space agencies are innovators and mass constellation owners could be the early adopters, according to their characteristics.

The technologies related with deorbiting satellite are categorized into approaching, capturing and removing. These technologies differ a lot, which shows the emerging phase of solution. The TRL analysis shows that there are some technologies with high TRL (e.g. TRL of 9 for propulsion) but high cost, and that the new concepts of technologies, like EDT, harpoons and nets, are promising but still in the maturing phase.

The analysis on the efforts on developing technologies, made by both academic circles and industries, show their different preferences. The hot topics in academic circles are tether, laser and others. The tethers are argued as the most promising technology to lower the cost of deorbiting system to a level of $400/kg on average, which might be the reason why tether is the most popular technology. The efforts from different countries shows that there is no technology convergence in this field. It justifies the emerging phase of deorbiting technologies.

The feasibility analysis shows that DRL, TRL and price are critical for commercial deorbiting services. As for the commercialization of innovation, deorbiting market is currently a demand-pull one. To mature this industry, the hybrid of demand-pull and technology-push needs to be taken into consideration. The strategies for different potential customers need to be customized. It is feasible to have a market of several kinds of potential customers. The pricing policy for new entrants is critical in terms of fundraising and investment attraction and competition for contracts.

To better understand the status and circumstance of commercial deorbiting service, a case study of ESA’s efforts on deorbiting EnviSat is carried out. ESA’s EnviSat case is the only case for commercial deorbiting service. The stakeholders, DRL of ESA, TRL of the technologies involved, the feasibility of the project are discussed, which shows that it is feasible for ESA to purchase a commercial deorbiting service in the near future.

According to all the analyses above, commercial deorbiting service is feasible in the future. Differentiated approaches for external factors are supposed to be implemented successfully to mature the customers. To those who have interests to provide commercial deorbiting services, four recommendations are given. The maturity of customers’ demands is the priority in commercial deorbiting market. The key words for technological solution is low cost, which enables a competitiveness. Technologies can’t be ignored in innovation business program. An appropriate pricing policy can be attractive for investors and potential customers. For new entrants without enough investment, it can also enable them to be approached by capital. Being sensitive with all the probabilities is the key in catching fleeting opportunities and minimizing the risks.

Acronyms

ADR	Active Debris Removal
CNES	Centre national d'études spatiales
CONOPS	Concept of Operations
COPUOS	Committee on the Peaceful Uses of Outer Space
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DRL	Demand Readiness Level
EDT	Electro Dynamic Tethers
EOL	End of Life
ESA	European Space Agency
EU	European Union
FOM	Figure of Merit
GAFAM	Google, Apple, Facebook, Amazon, Microsoft
GEO	Geosynchronous Earth Orbit
GTO	geostationary transfer orbit
IAA	International Academy of Astronautics
IAASS	International Association for Advancement of Space Safety
IADC	Inter-Agency Space Debris Coordination Committee
IAF	International Astronautical Federation
ISI	Inter Service Intelligence
ISL	Institute of Space Law
ISO	International Organization for Standardization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
KITE	Kounotori Integrated Tether Experiments
LEO	Low Earth Orbit

LIDAR	Light detection and Ranging
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
OECD	Economic Cooperation and Development
OOS	On Orbit Servicing
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
R&D	Research and Development
SSTL	Surrey Satellite Technology Limited
TRL	Technology Readiness Level
UCS	Union Concerned Scientist
UN	United Nations
UNO	United Nations Organization

1 Introduction

The aim of the research is to investigate and study the potential market of deorbiting end-of-life LEO satellites. As space activities increase, the population of space debris and end-of-life satellites are continuously increasing. Especially for the LEO sector, it is gradually crowded, raising the possibility of collisions. The Kessler syndrome, proposed by NASA scientist Donald J. Kessler in 1978, is an expanding concern internationally, after the Cosmos-Iridium collision issue in 2009. Satellite Squared Ltd. proposed this topic to Toulouse Business School, as an MCTP project to study the maturity of the market.

In past years, many scientists, specialists and engineers participated in the research on relative topics, and flourishing essays were published to show the result of latest progress. However, they mainly focused on technology, and rarely on market or business opportunities. Previously, one MCTP team from Toulouse Business School did the relative analysis on deorbiting space debris (Oliver and Pugliese 2015). They tried to demonstrate the market opportunity of deorbiting debris, with analysis on legal, political and economic aspects. Meanwhile they asked some questions to guide the discussion, and then their conclusion was the market was uncertain based on their research. Another team from Toulouse Business School processed similar research regarding such a topic in 2016 (Ruffiot and Baudet 2016). They built a business model for Active Debris Removal (ADR). They analyzed economic threat, legal & political barriers, and technical & economic barriers; and involved value chain of space market (stakeholders) as well. Finally, they proposed the solution to implement strict international jurisdictions to create the deorbiting market and to make it profitable via tax system involvement. The former research involved a lot of factors in terms of commercial deorbiting service. But, those researches didn't give a clear picture of its market potential and the evolutions of the market in the future.

This report will discuss this issue from an innovation project's perspective by implementing key tools. It starts with the description of market potential in terms of commercial deorbiting service. A PESTEL analysis is used to demonstrate the driven factors and the obstacles faced by stakeholders to join in deorbiting activities. The innovation diffusion model is discussed in this report to find out if this market is demand-pull or technology-push. Demand Readiness Level and Technology Readiness Level are analyzed and combined to find the approaches to mature the market. The feasibility analysis is implemented to find the keys to mature the market. To better understand this market, a case study of ESA's efforts on commercial deorbiting services (the only demand-pull project in the market) is discussed. At the end, the suggestions for commercial service providers are developed after the conclusions.

2 Methodology

2.1 Research design

Our understanding of the topic is a business analysis related to innovation. To find the answer, customer demand and technology supply need to be analyzed together.

The demand of customers is driven mainly by external factors, because deorbiting activities are a cost without any commercial benefit to customers. Therefore, an analysis of stakeholders and external factors is implemented to study the drivers for different potential customers, which is further discussed to find out the maturities and key external drivers.

From the supply side, technology is developing, and several methods of deorbiting are proposed by experts, some even go into experimental phase. China and Japan did the relative research in space separately.

An analysis of combining demand and supply is used to determine the feasibility of deorbiting market, which is the foundation for drawing the conclusions and recommendations for the business study.

2.2 Sources

A primary source is an artefact, a document, diary, manuscript, autobiography, a recording, or any other source of information that was created at the time under study. It serves as an original source of information about the topic.

A secondary source is a document or recording that relates or discusses information originally presented elsewhere. It involves generalization, analysis, synthesis, interpretation, or evaluation of the original information.

In our research, the information regarding demand is limited, so we conducted several interviews to understand the status of demand from different stakeholders (Appendix A shows the list of interviews). All of them are primary sources for our research. Information from interviewees is always their personal perspectives, known as empirical framework. As for the analysis of supply, universities, space organizations and relative companies always conduct frontier research. A lot of articles related to our subject are published. These sources are secondary sources for our research known as academic sources. Table 1 shows the contributions of sources for this research.

Table 1 contributions of sources for different parts

Contribution	Interview	Article	Website
Market potential	★★	★★	★★
Stakeholders and PESTEL	★★★	★★	★★
Demand analysis	★★	★	★
Supply analysis	★	★★★	★
Feasibility analysis	★	★	
Case study	★	★★★	★★

2.3 Research methods and tools

To implement the research, several research methods are picked for standardizing the process.

2.3.1 PESTEL

PESTEL is a strategic tool analyzing the Macro-environment to understand the external impact on strategy planning or market research. Our subject is a business analysis, so PESTEL can provide a helicopter view to support the research. PESTEL analysis includes 6 aspects to describe the impact on the market research, namely political, economic, social, technological, environmental and legal.

1) Political factors identify government influences on business environments or a certain industry
2) Economic factors determine how economic performance may impact the market or business in a long term.
3) Social factors include culture, demographics, and population to analyze the impact on market.
4) Technological factors involve innovations in technology to determine the impact on business development.
5) Environmental factors consider the surrounding environment, including climate, ecology, and geography etc, effecting on business market.
6) Legal factors are certain laws implemented by different countries in business activities, which bring certain impact on market.

2.3.2 Demand Readiness Level (DRL)

The “Demand Readiness Level” is a new measure to assess the maturity of evolving demands identified by potential innovation actors towards an appropriate stage of conceptualization of the need in the market (Paun 2011). It allows a matching point with scientific research teams capable to either propose as solution an existing scientific result through technology transfer process or translate the demand in new R&D projects. Table 2 shows the definitions of DRL.

Table 2 Demand Readiness Levels Summary

DRL	**Level Description**
1	Occurrence of a Feeling “something is missing”
2	Identification of a specific need
3	Identification of the expected functionalities for the new Products/Service
4	Quantification of the expected functionalities
5	Identification of the systemic capabilities (including the project leadership)
6	Translation of the expected functionalities into needed capabilities to build the response
7	Definition of the necessary and sufficient competencies and resources
8	Identification of the Experts possessing the competencies
9	Building the adapted answer to the expressed need on the market

2.3.3 Technology Readiness Level (TRL)

The Technology Readiness Level (TRL) scale was developed during the 1970-80’s. The National Aeronautics and Space Administration (NASA) introduced the scale as “*a discipline-independent, program figure of merit (FOM) to allow more effective assessment of, and communication regarding the maturity of new technologies*”. In the middle of the first decade after 2000, the scale was widely adopted as a system to define the readiness of technologies throughout the international space development community. Instruments and spacecraft sub-systems technical maturity with respect to a specific space application are classified according to a "Technology Readiness Level" (TRL) on a scale of 1 to 9. ESA is utilizing the ISO standard 16290 Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria assessment[1]. Table 3 gives the description of each level of TRL, which is the standard of estimating the technologies.

Table 3 ISO Technology Readiness Level Summary

TRL	Level Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard functional verification in laboratory environment
5	Component and/or breadboard critical function verification in relevant environment
6	Model demonstrating the critical functions of the element in a relevant environment
7	Model demonstrating the element performance for the operational environment
8	Actual system completed and accepted for flight ("flight qualified")
9	Actual system "flight proven" through successful mission operations

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[1] http://sci.esa.int/sci-ft/50124-technology-readiness-level/

2.3.4 Bibliometrics

To better understand the topic of a specific field, people can create a series of databases related to knowledge domains, and generate chronological maps of subject (topical) collections resulting from searches of the ISI Web of Science (Garfield 2004). The trends of research topics in recent years can reflect the interest of both academic and industrial organizations. By using bibliometrics analysis, we can identify the perceived challenges in the academic circle. For the bibliometrics analysis, The HistCite system can help users evaluate the output of topical and citation-based searches (Garfield and Pudovkin 2003). For identifying hot topics in deorbiting technology, only keywords related to deorbiting remain. To implement the methodology, we use the following process:

1) Search relative articles in academic database(s)
2) Formulate a standardized datasheet
3) Count the repetition of keywords by using HistCite
4) Pickup meaningful keywords related to the topic
5) Categorize keywords in similar meanings
6) Rank the keywords from high to low

2.4 Main phases of the project

To organize the whole research process, the research is divided into 7 phases (see Appendix B).

3 Market Potential Analysis

The analysis is performed using the Union Concerned Scientist (UCS) satellite database[2] published on 07-01-2016. The data available in this database is considered as one of the most trusted sources of information. This database covers many aspects of information related to all the satellites present today in outer space like mass, power, launch date, expected lifetime, user, operator, owner and manufacturer etc. The scope of studies is restricted to LEO satellites for the purpose of analysis.

To gain a better understanding, it is essential to know that this part follows the "Funnel approach" as it narrows down the scope of studies step by step. Starting with the big picture of the overall space industry that includes satellites from Geosynchronous Earth Orbit (GEO), Medium Earth Orbit (MEO), Elliptical Orbit and Low Earth Orbit (LEO), it eventually reaches to non-functional non-military commercial satellites mostly used for communication.

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[2] http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.WPy7GddSmHZ

As shown in Table 4, the analysis is performed mainly in **5 levels** corresponding to **3 degrees** of categories which allows to focus on desired market.

Table 4 Funnel Approach

First Degree	Level 1	Global Scenario	**LEO satellites**	**Non-Working**
	Level 2	Working / Non-working LEO satellites		
Second Degree	Level 3	Military / Non-military	**Non-Military**	
	Level 4	Working / Non-working Non-military		
Third Degree	Level 5.1	Non-working non-military LEO (User)		
	Level 5.2	Non-working non-military LEO (Purpose)		

It is very important to know that there are many satellites in the LEO mostly sent by countries like China and Russia, with very limited information available. The category used to identify these satellites is NO INFORMATION / NO DATA satellites for clarification purposes. It allows readers to refrain from assuming average expected life which might not be true in every case. It also helps to minimize the risks aroused by assumptions which eventually could lead to wrong direction.

3.1 Level 1: Global scenario of space.

This is very basic **first degree** of analysis which can be used to get a general idea of the current scenario in the space. As shown in Figure 1, the satellites in GEO are almost 36% of all the satellites and are second largest in numbers. The Elliptical and MEO satellites are very few in numbers and LEO satellites are the most popular ones with highest of 55%. This makes LEO very challenging space for satellite operations. These numbers of satellites will definitely be increasing in coming years. This shows that there is an immense potential for deorbiting services in LEO

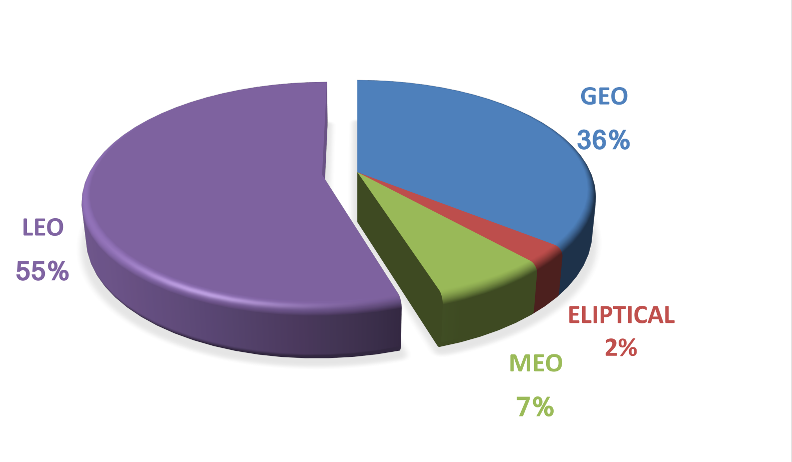

Figure 1 Global scenario of Space

3.2 Level 2: Low Earth Orbit (LEO) satellites

To better analyze the potential of results from the first degree and to take it to the next level, it is very important to analyze the LEO satellites even further. This is performed by understanding working and non-working that is end of life (EOL) satellites among all the satellites in LEO. To calculate the life of satellite, the best possible way was to consider date of launch and useful life of the satellite. Here, many satellites do not have data available regarding their useful life as most of the LEO satellites are suspected to be spy satellites and not registered with authorities. In that case, a new category “NO INFORMATION / NO DATA” is created as mentioned earlier. It is very difficult to identify actual number of End of Life satellites as in most of the cases these satellites are being used even after their mentioned useful life. The studies performed in this article are based on deorbiting services, it is essential to assume and believe estimated life as a prime parameter for further analysis.

The total number of LEO satellites are basically divided into functional and non-functional categories. This helps to get a helicopter view of targeted potential market for deorbiting services. Not to mention separately, every satellite in space today working or non-working is required to be taken care of after its useful life or malfunctioning. These satellites cannot be abandoned in space because they could be potential risk for other satellites as they move very fast. Any collision at such a high speed can cause huge damage which can ultimately lead to creation of large number of debris in the space which in turn increases the risk of collision (Kessler Syndrome).

From Figure 2, it is visible that “No Information” category is almost 44% and it restricts scope of the study. Though at present any information about these satellites is not available but for sure some of them have already expired and remaining will expire soon. Hence, the study of necessity of deorbiting services stands true even for them in the future.

Considering the present available situation and leaving the satellites with no information available aside, almost 37% of satellites present in the LEO today are already expired and are occupying space unnecessarily. The remaining 19% will expire soon as these satellites have very short to medium expected life or most of them are mission specific.

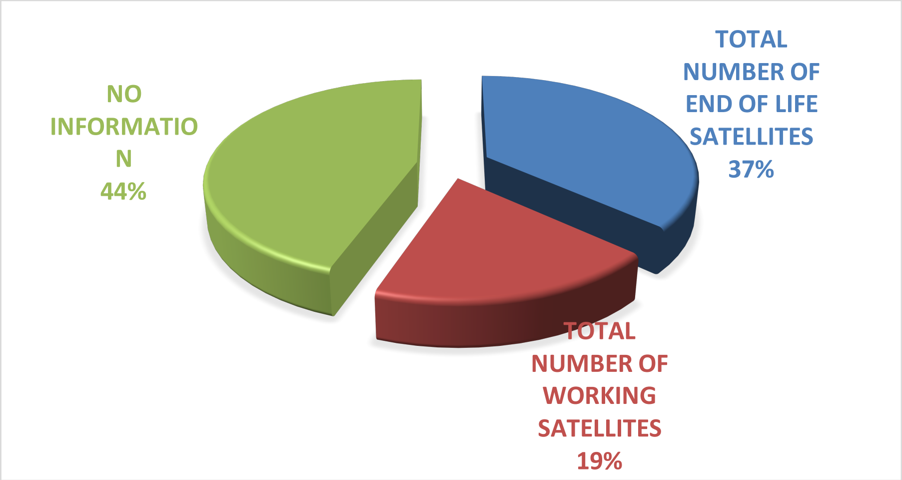

Figure 2 Differentiation based on Working / Non-working satellites in LEO

3.3 Level 3: Military and Non-Military satellites in LEO

This is a second degree of analysis, as it deals with the LEO satellites one step further. After having an overview of targeted segment, this part talks about the number of Military owned satellites and Non-Military satellites. This helps in further narrowing the scope of market. At first, it seems very difficult to deal with Military satellites because of their confidentiality and rules and regulations, hence concentrating only on Non-Military sector as a potential market makes sense. It is very important to know exact practically possible users to target. As shown in Figure 3, almost 80% of the satellites are owned by enterprises / organizations other than military.

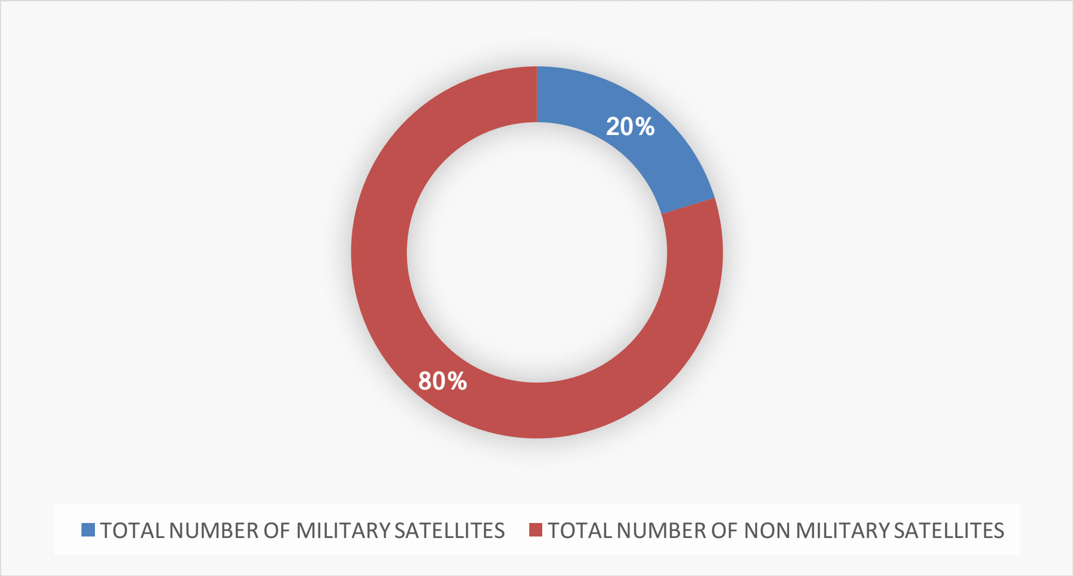

Figure 3 Differentiation between Military & Non-military satellites in LEO

3.4 Level 4: Non-military LEO

After narrowing down the potential market to non-military LEO satellites, it is better to know the working, end of life and no data available satellites to have a better sense of situation. Figure 4 shows many non-military satellites present in LEO today are already expired. These satellites are occupying LEO and are potential threat to future of upcoming space explorations. It can be beneficial for new or existing space actors to reduce future collision risks by deorbiting these satellites.

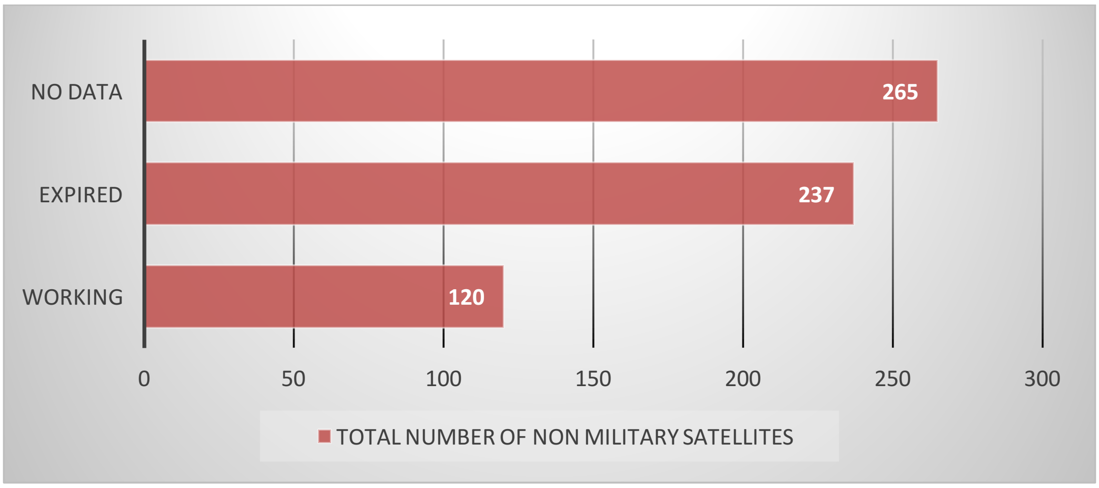

Figure 4 Differentiation based on Working / Non-working non-military satellites

3.5 Level 5: Total number of Non-Military satellites

3.5.1 Level 5.1: Total number of Non-Military satellites (user based)

It is essential to further classify the Non-Military LEO satellites on the basis of Users. The Non-Military sector is very vast and consists of many users like Government, Civil, commercial and Jointly owned satellites (Figure 5). Every single actor in this category is important and plays a specific role. From this categorization, commercial users are in large number within Non-Military satellite category. This part of analysis gives very general and superficial idea of potential targets for commercial deorbiting services.

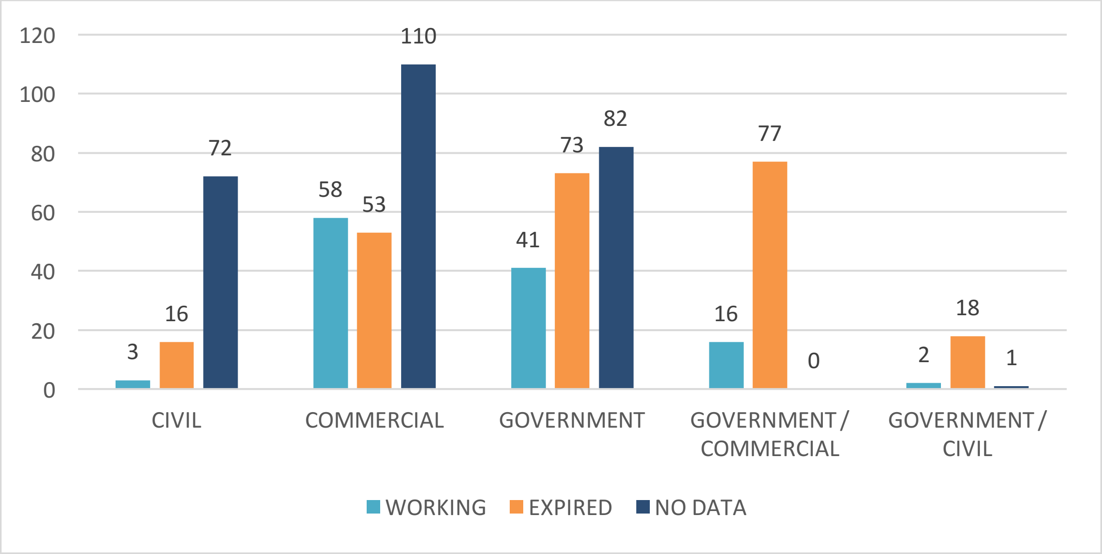

Figure 5 Differentiation based on primary users (Non-military satellites)

3.5.2 Level 5.2: Total number of Non-Military satellites (Purpose based)

Even in Commercial category, there are many sub categories related to purpose of use of satellites like communication, earth observation, earth / space science, space observation, technology development / demonstration, communication / technology / maritime, earth observation / technology / communication / space (Figure 6).

To go even further, it requires **third degree** of analysis which helps in further narrowing the choice of market to target. From the study, it is observed that, communication is the most common purpose for the satellite users.

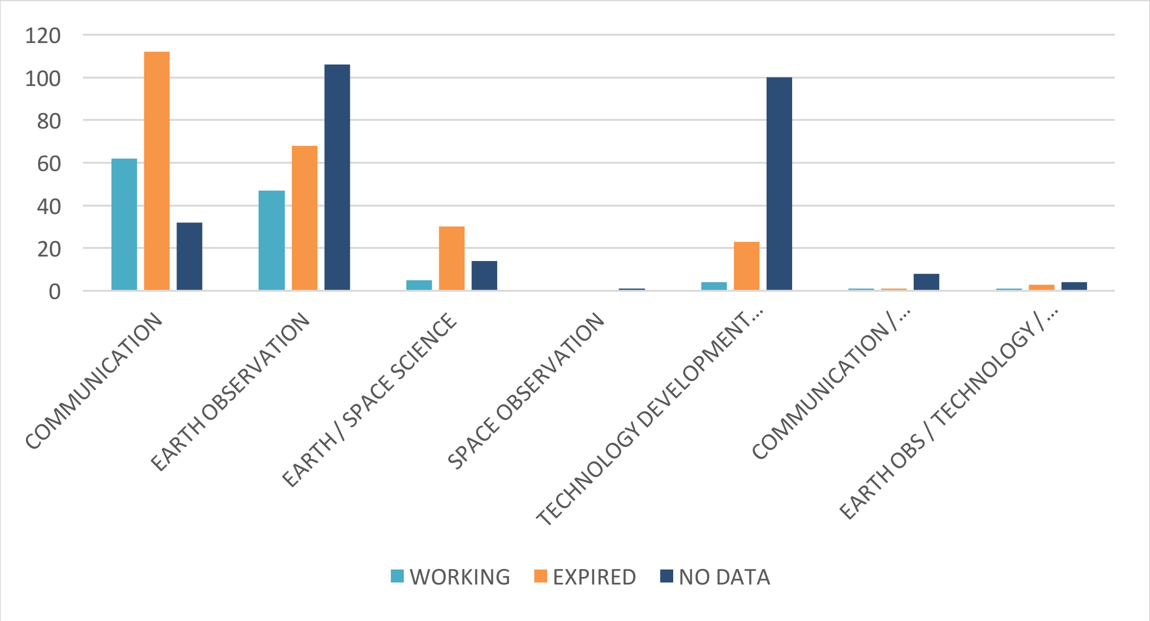

Figure 6 Differentiation based on primary purpose (non-military satellites)

Though the market analysis mentioned above leads to Communication satellites owned or operated by commercial users from non-military players, it is very difficult to target them as a primary user of deorbiting services as each of them has some limiting factors. Until today, no rule forces any user to deorbit their own satellite makes this service non-priority.

3.6 Analysis based on Mass

Figure 7 shows the analysis made depending upon the launch mass of satellite as the choice of technology to be used for deorbiting satellite service highly depends upon the mass of the satellite.

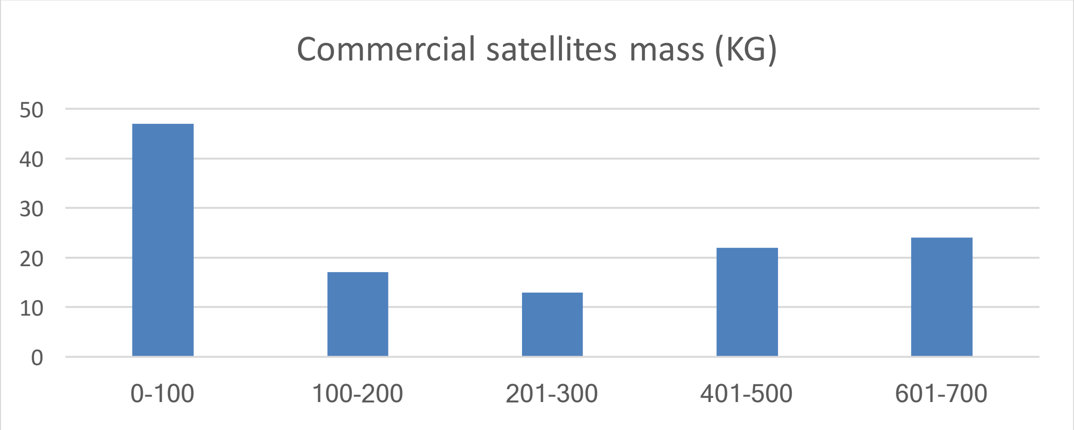

Figure 7 Non-military commercial satellites mass (in Kg)

3.7 Forecast

Figure 8 shows the number of satellites expiring in the next 20 years based on information available as per the UCS database. It is also shows that the number of LEO satellites reaching expected useful life is increasing almost every year. Considering the satellite constellation projects like OneWeb and Iridium next, there will be a huge number of satellites in LEO in the near future. That will make services like deorbiting of End of life satellites a major necessity as mentioned above.

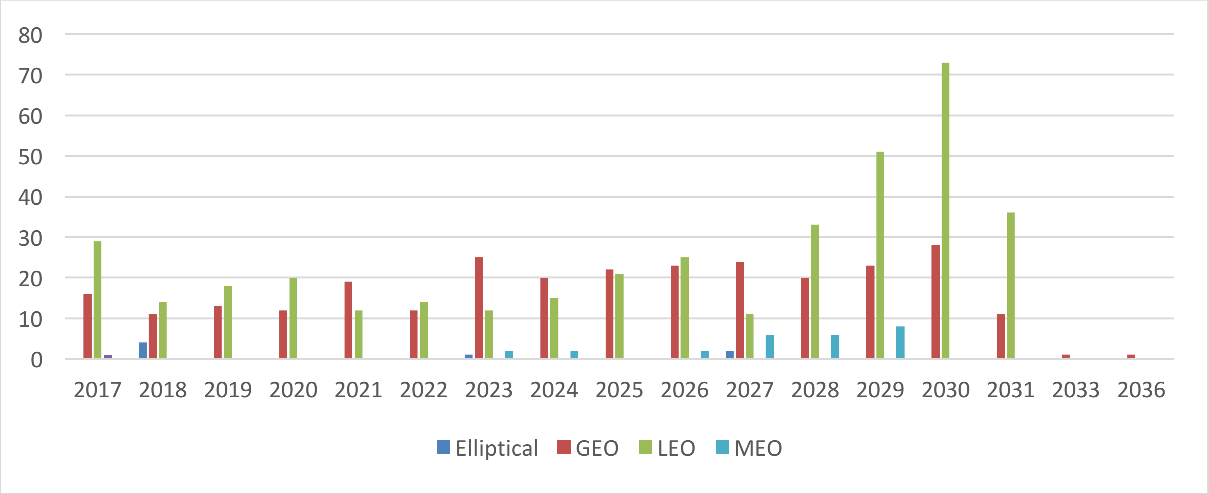

Figure 8 Forecast for the next 20 years based on information available today

With the commercialization of space activities, notably in the telecommunications sector with the launch of constellations from OneWeb and SpaceX in LEO, the risk of collisions would significantly increase. With these types of constellations being on a similar orbit, the threat of debris is a danger to their own constellations. It is therefore important for these commercial space companies to de-orbit to protect their own assets but also to respect other country's regulations[3]. The market potential will be much higher if the commercialization of mass constellations is materialized in the future.

3.8 Conclusion

The analysis above shows that the market potential is quite high in terms of commercial deorbiting service.

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[3] From the interview with Cedric Balty, Thales Alenia Space, on March 20, 2017.

4 Stakeholder Analysis and PESTEL

It is now necessary to shed light on the factors and drivers that are likely to exert influence over LEO satellites' owners and operators demand for deorbiting. These factors can be distinguished between two main categories:

- Key drivers among space stakeholders playing in favor or against LEO satellites' end-of-life disposal through deorbiting
- External factors that shape and influence LEO satellites' end-of-life disposal

This section will further examine these two categories of factors through stakeholders' and PESTEL analyses. Once done, this approach will facilitate the identification of potential customers for deorbiting servicing linked to LEO satellites.

4.1 Space stakeholders and their key drivers

The difference between commercial deorbiting service and other commercial space programs is that it has more connections with all the traditional participators in space sectors. It is not as independent as other commercial space programs. Table 5 shows the stakeholders related to commercial deorbiting services.

Table 5 stakeholders in terms of commercial deorbiting services of LEO satellites

#	Stakeholder categories	Stakeholders
1	Governments and political regulators	Governments
2		Government space agencies
3		Office of Outer Space Affairs composed of the COPUOS
4		Inter-Agency Space Debris Coordination Committee (IADC)
5	Owners	Operators (owners)
6	manufacturers	Satellite manufacturers
		Deorbiting service providers
7	Others	Insurers
8		General public

For our analysis, we will shed particular light on:

- Governments and political regulators
- Governmental/intergovernmental space agencies
- LEO satellites' operators and manufacturers
- Satellites' insurers

Below, a short description of each stakeholder is detailed, and followed by their positions regarding LEO satellite EOL disposal (details in appendix C to E).

4.1.1 Governments and political regulators

Space activities are essentially structured and shaped by public and private actors. Regarding its political environment, the space sector is highly dependent on two kinds of actors playing a major political role, though uneven regarding its potential political influence.

Historically, States were the first Space players, if one refers to the first North American, Russian and Chinese space expeditions from 1957 onwards. After the end of the Cold War, and despite a relative detente between nations, Space has still been deemed a strategic activity to demonstrate national sovereignty and power to the international community.

At nations' level, political actors likely to influence space activities are thus space-faring nations and also non space-faring nations who could be owners of satellites without having the facilities to manufacture and launch them. Yet, as effective or potential clients of satellite manufacturers and operators, their influence on space activities is high. So, they should be taken into account in this reflection, just like regional organizations, like the European Union through its executive body, the European Commission.

Over time, the community of space-faring States has enlarged, which, very early, triggered the necessity to regulate space activities at an international political level. Since 1959, the United Nations, through its Office of Outer Space Affairs composed of the COPUOS (which is itself subdivided between a Scientific and Technical Subcommittee and a Legal Subcommittee) has played this role.

National space agencies can also be considered as political actors in the sense that they are funded by a nation and thus, are highly dependent on domestic budgets. Since their interest can slightly differ from their funding nation's, they have been distinguished in the present analysis.

Finally, multilateralism in international space activities has led to the creation of specialized transversal regulatory bodies that also play an important political role in shaping space policies. The Inter-Agency Space Debris Coordination Committee (IADC) is one of them. Its visibility, though rather institutional, is quite considerable and thus, also impacts space activities through the common actions of international and national space agencies as well as of other spaces actors (space-faring countries, satellites owners, operators and so on).

Though political institutions consider space as a strategic sovereign function, space debris mitigation is not positioned in the top hot issues in their agendas. Space agencies have a high interest and a crucial influence of space debris mitigation, but they process in a quite fragmented way without cooperative policies in this regard. Appendix C shows the position of political actors and regulators.

4.1.2 LEO satellites operators and manufacturers

4.1.2.1Operators in LEO

Here, operators are understood as satellites' owners able to exploit them. Next to governmental and military satellites, LEO also shelters private operators' satellites, whose owners are: Iridium, PlanetLab, GlobalStar, Orbcomm, Aprize Sat, Aerospace Corporation etc. And soon OneWeb. These operators are the first target of potential on orbit and deorbiting services. They are entitled to decide if they are willing to extend the life of their satellites in orbit or to determine the type of end-of-life disposal they will implement for their decommissioned satellites. In this sense, they constitute an important category of stakeholders.

4.1.2.2Satellites manufacturers

In the case of a market emergence of on orbit and deorbiting servicing, satellite manufacturers would also play a determinant role in the design, manufacturing and launching of new deorbiting and on orbit servicing devices. Yet, as Ellery, Kreisel and Sommer explain, they "*tend to react to the perceived needs of the satellite operators*" (Ellery, Kreisel, and Sommer 2008).

This being stated, it is important to further analyze the level of interest of these stakeholders with regards to LEO space mitigation and, more precisely, to deorbiting and on orbit servicing.

If satellite manufacturers believe deorbiting technologies' maturity is currently too low, they tend to follow the will and needs of satellite operators. Yet, they are interested in producing deorbiting satellites if the need emerges. As for them, satellite operators are crucial to trigger market pull. But, they argue that the cost of deorbiting is still too high for them to buy it. Appendix D details the perspectives of operators and manufacturers.

4.1.3 Insurers for LEO satellites

Space insurers represent a niche (40 companies worldwide), though considerably important and competitive market with regards to the amount of insurance premiums related to space launches (first party contracts), in-orbit life and third-party insurances. The space insurance market's growth is also highly volatile, which is tightly linked to the safety of space operations on the ground (launches) and in-orbit (satellites' orbital life).

This common interest in insuring LEO constellations reveals that space insurers' position regarding LEO satellites' deorbitation is relatively a "wait-and-see approach". While they admit there is definitely a need and a market for deorbiting technologies, they often raise the question of the willingness to pay for it.

As risk adverse, insurers judge that deorbiting servicing is not yet a mature market. They made it clear they would request high insurance premium to compensate the risk, may deorbiting servicing operations be developed. They could be interested in insuring deorbiting satellites (for further details, please refer to appendix E).

4.1.4 Conclusion

As a matter of conclusion of this subsection, Table 6 offers a synthesis of the stakeholders' analysis just carried out.

Table 6 Stakeholders’ interest and power with regards to deorbiting services

Stakeholder	Description and Details	Interest	Power
Governments	Though political institutions consider space as a strategic sovereign function, space debris mitigation is not positioned in the top hot issues in their agendas.	Low	High
Government space agencies	National and regional space agencies such as ESA, NASA, JAXA, CNSA, or JAXA… They have a high interest and a crucial influence of space debris mitigation, but they process in a quite fragmented way without cooperative policies in this regard.	High	High
Space related civil research institutions	Research institutions have published a considerable amount of research papers regarding deorbiting services.	High	Low
Satellite manufacturers	If satellite manufacturers believe deorbiting technologies’ maturity is currently too low, they tend to follow the will and needs of satellite operators. Yet, they are interested in producing deorbiting satellites if the need emerges.	Low	Low
Satellite operators	If satellite operators are crucial to trigger market pull, they argue that the cost of deorbiting is still too high for them to buy it.	High	Low
Deorbiting service providers	Involved in providing deorbiting servicing.	High	Low
Insurance companies	As risk adverse, insurers judge that deorbiting servicing is not yet a mature market. They made it clear they would request high insurance premium to compensate the risk, may deorbiting servicing operations be developed. They could be interested in insuring deorbiting satellites.	Low	High
Legal regulatory bodies	International and legal regulatory bodies have been considerably involved in space debris mitigation for more than a decade now. Yet, the guidelines they produced are non-binding and legal experts do not see any regulatory improvements in LEO debris mitigation.	Medium	Low
General public	The public awareness regarding space debris mitigation is very low. Unless populations push for more responsibility to their governments, their influence in that matter remains quite limited. Yet, theoretically, their power is quite considerable.	Low	High

4.2 External factors influencing stakeholders (PESTEL analysis)

This section gives, through a PESTEL analysis, a snapshot of the influence of political, economic, social/sociological/technological, environmental and legal factors likely to have a direct or indirect influence on LEO satellites’ end-of-life disposal, and particularly on the demand and the technological maturity of deorbiting servicing projects.

4.2.1 Political factors influencing deorbiting servicing

The relative democratization of space launches over time has led to an exponential increase of satellites in geostationary, medium and low orbits. Building ambitious space policies appear strategic to nations or transnational organizations like China, the US, or the European Union. In that matter, the current political context makes it difficult to predict the medium-term orientation of space policies. In the US, the recently elected Donald Trump, still expected to nominate the new head of NASA, is still silent concerning the orientations he is willing to give to US space policy[4]. In Europe, Brexit has triggered uncertainty on the future national space strategy of Great Britain, despite the clear will of the country to capture 10 % of the global space market by 2030. As ESA declared in September 2016, though leaving the EU, Britain would still remain a member of the European Space Agency, but on renegotiated terms to ensure its participation in certain projects[5].

4.2.2 Economic factors

It is well-known that space policies tend to be deemed strategic by space-faring nations, often constituting the first budget in their portfolios. In 2017, NASA's budget reached unexpected amounts ($19,5bn), just like ESA at its own scale, with $10bn in for the triennial contract 2015-2018. According to the OECD, China's space budget reached $6.1bn in 2013, one billion more than Russia ($5.2bn).

While geostationary orbit for a long time remained the favored market of private actors, leaving LEO to institutional and scientific operators, the trend has been changing these last few years. In 2013, during its workshop dedicated to active debris removal, the International Astronautical Federation (IAF) reported that the total benefits accumulated in LEO only amounted $ 3 billion, compared to $280 billion for GEO. Yet, a US study related to the economic development of US Low Earth Orbit sector shows that the capital invested between 2010 and 2014 through Venture Capital reached $284 million, against "only" $89 million between 2000 and 2004 (p.89). Since 2008, over $250 million of equity have been invested in miniature LEO satellites, and over $1 billion in launch vehicles[6]. The Low-earth orbit seems to be more attractive than before.

Space agencies, such as NASA, have confided a growing part of their space activities and projects to private actors through public-private partnerships. Since 2008, "*NASA's decision to buy service performances (launches, satellite data…) and to confide space vehicles' development to private partners who would be free to sell them to other clients, is the first*

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[4] Swarts Philip, "Budget to be first indication of Trump's space priorities", Space News, January 26th, 2017.
[5] "Brexit will change UK role in Europe's space programs: ESA", *AFP*, September 14th, 2016, https://lc.cx/J8ny
[6] Lerner, Josh, Leamon, Ann, & Speen, Andrew. 2016. "Venture Capital Activity in the Low Earth Orbit sector". In *Economic development of Low Earth Orbit*. Edited by Besha, Patrick and MacDonald Alexander for NASA. 100. https://lc.cx/JjSq

trigger factor of the space industry's mutation[7]", Rachel Villain, Key advisor and co-founder of Euroconsult , says[8]. This new tendency gives a new perspective for the commercial service in space sector.

Appendix E details the status of insuring market for space sector.

4.2.3 Social and Technological factors

From the space industry's perspective, the analysis of technological factors influencing the development of deorbiting technologies and services cannot be carried out without considering the simultaneous social phenomena taking place in this industrial field.

For a few years now, the space industry has been penetrated by a new category of economic actors that did not possess, space competences, but rather technological capabilities and marketing resources that have allowed them to adapt and reshape the space sector thanks to new standards.

The emergence of the so-called GAFA (for Google, Apple, Facebook, and Amazon, but one could also add Paypal) in the 2000's has propelled their leaders in the spotlight of the economic and media worlds. Interestingly, as Rachel Villain explained, the entrance on stage of these "*Apollo orphan billionaires*" has been crucial for the space industry. Along with their entry in the space industry, they bring a new range of value paradigms, not based on national stakes or immediate technological resources anymore, but rather on long-term competitiveness and immature but high potential technological capabilities. Quite well-known by the general public thanks to their medias and marketing *coups*, they are exporting their social, media and economic capital in the space industry. This sociological phenomenon, which can be deemed a declination of Pierre Bourdieu's so-called concept of "*social defector*", has one obvious advantage: permitting the general public to better understand and interest themselves in space issues. Hopefully, this could, in the mid-run, bring in the public sphere the very serious question of space pollution.

Along with their entry in the space industry, they bring a new range of value paradigms, not based on national stakes or immediate technological resources anymore, but rather on long-term competitiveness and immature but high potential technological capabilities.

The success of their business models and the economic value withdrawn from their products and services have permitted them to accumulate huge amounts of cash.

Thanks to it, new space entrants (essentially start-ups) are emerging and proposing new innovations to the industry, notably regarding on-orbit servicing and deorbiting technologies (Orbital ATK in the US, AstroScale in Singapore, D-Orbit in Italy, Orbital Satellite Service AB (Sweden), or GEO Ring Services (Greece). In reality, the progressive and still pending development of technological demonstrators by national and regional space agencies has

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[7] Rachel Villain, Euroconsult co-founder, cited in « *Les géants de la tech bouleversent le marché spatial* », Le Figaro, December 28th, 2016.

[8] Ibidem

considerably helped them grow. One can notably mention JAXA's autonomous rendezvous and docking demonstrator in 1997, DARPA's autonomous spacecraft refueling and servicing techniques in 2005, or ESA's European Robotic Arm in 2005. As explained by Christophe Bonnal, Senior Space Expert in CNES, "*once these technologies are developed, they are to be provided to the ones who will be able to use them to propose space cleaning services without bearing their development costs*" [9].

As we will see in the second part of this research, the technologies linked to deorbiting missions, though evolving between a TRL of 4 to 7, do not yet have the configuration permitting them to be easily adopted. Indeed, their non-cumulative and discontinuous nature represent a considerable obstacle to adoption. Besides, as demonstrated in the previous stakeholders' analysis section, LEO satellite operators currently tend to favor punctual manoeuvers thanks to the development of Space Situational Awareness Technologies, despite the fact that those technologies are still to be improved for better efficiency.

4.2.4 Environmental factors

Ecological sustainability is another challenge for the space industry. Every space exploration campaign affects the environment. There are very few laws and legislations in place regarding this issue. If one considers the options available related to deorbiting services, there is still scope for major improvements. As mentioned in the social section of this PESTEL analysis, new actors entering this domain seem to be more sensitive to environmental issues.

This debris densification has become quite a serious environmental issue within the space community. Yet, not enough to create concrete reactions regarding space debris mitigation, such as deorbiting incentives. This could be explained by the famous so-called Kessler syndrome.

Considering space as an area to be protected from pollution is not a black and white reflection. Indeed, emerging deorbiting and debris mitigation technologies come along with their own environmental challenges, as it *"contributes to an extent in the biggest problem of global warming"* [10].

The constantly increasing demand related to environmental sustainability is the only option available to contribute in the growth of space industry. As the industry is moving steadily towards newer technologies like deorbiting may force authorities to think on development of legal framework.

Appendix F details the environmental issues.

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[9] Bonnal, C. *Pollution spatiale, l'état d'urgence*. (Paris, Belin, 2016), 206.

[10] Sayings withdrawn from the recorded interview of Romain Lucken, co-founder of Share my Space, in January 27th, 2017.

4.2.5 Legal factors

Space law remains in the scope of International Private and Public Law. Indeed, space law is of the United Nations' origin. The different treaties and conventions that have been signed in this frame rule the relationships with United Nation Organizations (UNO) and the signatory States. It is therefore under International Public Law scope. International and national private laws also play a significant influence in space activities.

These intertwined dimensions are responsible for space law's high degree of complexity. Several other factors contribute to it.

It is highly uncertain that international space law is going to contribute, in the near future, to the development of a deorbiting servicing market, unless, as suggested by Armel Kerrest, a collision between LEO satellites forces authorities to amend the international treaties. For Andrea Harrington, a move could actually be made by countries with regards to their internal national regulations. A few countries, like France, have already implemented more constraining space debris mitigation regulations, notably regarding deorbiting controlled and uncontrolled actions. But such initiatives are currently scarce and not coordinated.

Appendix G details the legal issue in space mitigation.

4.2.6 Conclusion

In light of the PESTEL analysis, one just saw how complex the space industry's global environment was. The previous stakeholders' analysis demonstrates that the willingness to pay for this service and to transform the concept into a beneficial business model seems to be dampened by a wait-and-see approach.

This phenomenon can be associated to a non-cooperative attitude. As developed all along the stakeholders' analysis, the reasons invoked for that are quite numerous: too expensive for operators, beyond insurers' professional scope, a lack of political will for legal regulators, etc.

Table 7 offers a synthesis of the external factors identified in the previous PESTEL analysis to facilitate the global understanding.

Table 7 PESTEL analysis: synthesis

Environment	Main factors mentioned	Potential Influence*
Political	▪ Global uncertainty in the Western world: newly elected Trump in the US, Brexit, Europe's political instability (rise of nationalisms) ▪ Intensified international competition, notably from Asia. E.g. China's Important investments in space industry ▪ National competition could influence the development of deorbiting technologies	++
Economic	▪ Raising interest of satellites' operators for Low-Earth Orbit segment ▪ E.g. capital invested by US venture capital in LEO satellites evolved from \$89 to \$284 millions in 10 years. ▪ Generalization of public-private partnerships between space agencies and private actors ▪ NASA's debate about commercializing or outsourcing SSA's technologies	++
Social	▪ Emergence of "social defectors" (Bourdieu) transferring their technological and marketing resources from high-technologies' sector (GAFA) to space sector. E.g. Elon Musk and Space X	++
Technological	▪ A new range of value paradigms: quest for long-term competitiveness through immature but high potential technologies ▪ Emergence of new space entrants (start-ups) willing to develop on-orbit and deorbiting servicing (more in GEO). ▪ Emergence of deorbiting technologies that are non-cumulative and discontinuous = obstacle to adoption ▪ SSA technologies to be yet improved	++
Environmental	▪ No binding law linked to space pollution ▪ 17,600 space objects in orbit (LEO, MEO, GEO) ▪ 94 % of the catalogued orbital population is composed of space debris ▪ LEO orbit particularly concerned by pollution (notably around 800km) ▪ Deorbiting a satellite involves negative environmental effects (oceans' pollutions, atmosphere' pollution)	-
Legal	▪ High complexity of space law layers ▪ A blurred legal frame of space and orbit delimitation ▪ No legal difference between a debris and a decommissioned satellite still in-orbit ▪ Absence of constraining clause regarding satellite registration ▪ Non-binding nature of international space laws ▪ No legal precedent regarding LEO satellites' collision (tacit agreement between countries preferred to court)	+

**Potential influence on LEO satellites' end of life disposal policies from -(no influence) to +++ (very high influence*

5 Evaluation and Analysis of Potential Customers

5.1 Identification result of potential customers

For commercial deorbiting service, the potential customers are clear because of the stakeholder analysis in the former chapter. A group of researchers discussed on-orbit servicing commercial opportunities, giving an enlightening view of potential customers (C. Johnson et al. 2014). Based on the previous stakeholders analysis , eight potential customers have been identified (Table 8). Some of them are owners of satellites, whereas others are not. For owners, purchasing deorbiting services means that they are taking responsibilities for themselves. For third parties, it means taking responsibilities for others by authorizations. The reason why they can be potential customers are presented together with the following "Evaluation of potential customers' DRL" section.

Table 8 identification of potential customers

#	Potential customers	Remark
1	Government space agencies	ESA
2	Other government space agencies	
3	Other government owners	Excluding space agencies
4	Mass constellation owners	
5	Other satellite owners	
6	UN COPUOS	
7	Space debris community	e.g. IADC
8	Non-Governmental organizations	

5.2 Potential drivers for maturing potential customers

Based on the PESTEL analysis, potential customers above can be influenced by external factors. Table 9 shows the potential drivers for each one and their probabilities to happen. The analysis shows that government space agencies and mass constellation owners are the most probable customers in the future.

Table 9 key drivers to DRL and their probability

Potential customers	**Key drivers to mature potential customer**	**Probability**
Government space agencies	Technological: the evolution of technologies will provide a mature and cheap solution for commercial deorbiting service	High
Other government space agencies	Political: Political pressure from other space agencies who contribute in deorbiting satellites Legal: Space laws Economic: the price of commercial deorbiting service is much lower than developing capability by themselves	High
	Environmental: Disasters caused by debris collision can make public more aware of the serious situation. Social: Public concerns on space debris will result in social pressure to governments, and then space agencies will take responsibility to pay for deorbiting services	Low
Other government owners	Political: pressure diffusion from space agencies. Other government owners need to pay by themselves. They will pay through space agencies, even though they are mature	Very low
Mass constellation owners	Economic: the risk of collision is high when a lot of satellites are in the same orbits. The success rate of deorbiting satellites, by embedded deorbiting functions, is about 90%. To ensure their assets, they will buy commercial services	Very high
	Legal: they need deorbiting service because of space law	Very high
	Technological: the progress of technologies boosts the development of mass constellations (new entrants), which makes the orbital resources more scarce. More owners of mass constellations will pay for the services.	high
Other satellite owners	Economic: pressure from early adopters who lower the deorbiting mission cost, because they are using space resources and early adopters are paying for the sanitary service	Medium
UN COPUOS	Political: Main space faring nations have political will to dominate space by charging deorbiting fee for existing satellites or for allocating orbital quota, making UNCOPUOS a platform to organize deorbiting mission Environmental: Disasters caused by debris collision can make it powerful and can organize international activities on removal	Very low
Space debris community	Environmental: Disasters caused by debris collision can make it powerful and can organize international activities on removal	Very low
Non-governmental organizations	Environmental: Disasters caused by debris collision can make public more aware of the serious situation. Social: Public concerns on space debris will result in some donation to NGOs to buy deorbiting services.	Very low

5.3 Evaluation of potential customers' DRL

Different potential customers have different maturities. The evaluation of DRL is mainly influenced by their status.

Government space agencies

Normally, government space agencies would like to try new technologies, and to fund cutting-edge technologies. ESA clearly expressed the interests for purchasing a commercial deorbiting service. So, the DRL for ESA is 7.

Other government space agencies

Other government space agencies have shown their interests about deorbiting satellites, but not by purchasing a commercial service, so their DRL is 3.

Other government owners

Other government owners (e.g. agricultural ministry) have limited awareness of space environmental issues like space debris, so there is little demand for commercial deorbiting service. Due to the close relationship between space agencies and other government owners, they could be a potential customer in the future.

Mass constellation owners

Because of the awareness of limited orbital resources as GEO satellites owners, OneWeb just expressed their interests about deorbiting end-of-life satellites by themselves not by commercial services. So, the DRL of mass constellation owners is 1. It is critical to be aware that the success probability of deorbiting is not 100%, then they will probably purchase a commercial service.

Other satellite owners

As all the satellites owners are aware of space debris, they could be potential customers. Yet, the current position of DRL is only 0.

UN COPUOS

UN COPUOS plays a vital role in international space environment protection. The legal system related to space debris is firstly developed by it. They are more aware of the situation. Even if it is a regulator, not a practitioner, there might be probability for it to implement space debris removal mission for extreme condition. Thus, it can be a potential customer.

Space debris community

Space debris community is dealing directly with space debris issues and regulations. They are more aware of the seriousness of the current situation. Similar with UN COPUOS, it has a chance to become a customer for extreme condition.

Non-Governmental organizations

Non-Governmental organizations are playing a significant role in environmental issues. The interaction between non-governmental organizations and the general public is the main source of social awareness about environmental issues. Similar with actions led by NGOs regarding global warming issues, there is a chance for them to finance or pay for space debris service under the support of public and private capitals. But, their current level of DRL is 0, because there are no NGOs caring about space debris issues.

Table 10 shows the results of the evaluation of DRL for those potential customers above.

Table 10 potential customers and their DRL

Potential customers	DRL	remarks
Government Space Agencies	7	
Other Government Space Agencies	3	
Government Owners	0	
Mass constellation Owners	1	For GEO satellites operators, 7
Other satellite owners	0	
UN COPUOS	2	
Space Debris Community	3	
Non-Governmental organizations	0	

5.4 Further analysis of potential customers

According to the adopters categorization on the basis of innovativeness (Rogers 1995), the adopters can be categorized into several categories (Figure 9). Considering the status of the commercial deorbiting market, it is still in the emerging phase, which means there are no actual markets. To illustrate the evolution of this market at the emerging phase, the analysis of innovators and early adopters are critical.

The space agencies (e.g. ESA) are the innovators because of their clear characteristics (first need for the new commercial deorbiting services, high expertise related to the products, tolerance to the risk, expectation for the unprecedented return of the product and their awareness of being pioneers).

The next customer category who has much larger demand will be early adopters. The analysis before shows that owners of mass constellations have the highest probability of becoming early adopters, because of their characteristics (purchasing the innovation after innovators, their lower expertise than space agencies, their average risk aversion, the success of the innovation embodied by them).

This analysis above shows that the emergence of commercial deorbiting service market is on the way because of the clear picture of innovators and early adopters.

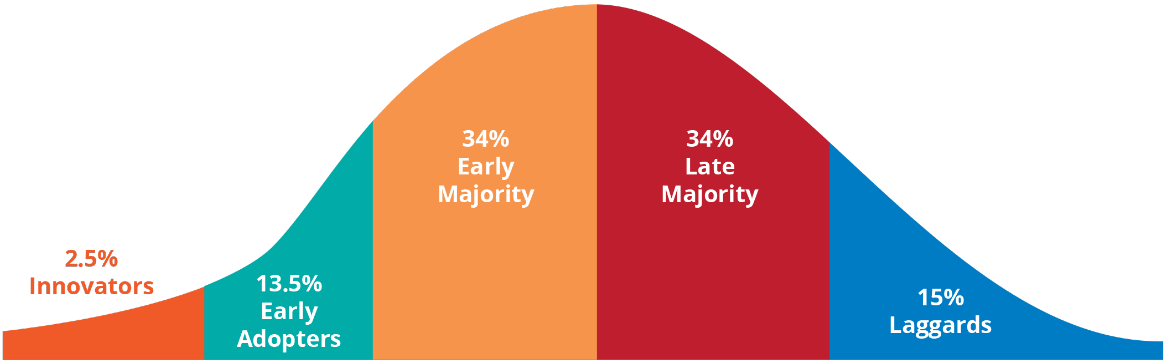

Figure 9 adopters’ categorization on the basis of innovativeness

6 Evaluation of Deorbiting Technologies’ Supply

6.1 Technology categorization

There are different methods to describe the procedure of a deorbiting mission. (Shan, Guo, and Gill 2016) use five phases: Launch and Early Orbit Phase (LEOP), far-range rendezvous phase, close-range rendezvous phase, capturing phase and removal phase.

(Bonnal, Ruault, and Desjean 2013) use five functions to describe the core technologies in deorbiting a satellite, namely:

1. Function F1: far-range rendezvous between chaser and debris
2. Function F2: short-range rendezvous between chaser and debris
3. Function F3: mechanical interfacing
4. Function F4: control, de-tumbling and orientation of the debris
5. Function F5: deorbitation

Different researchers give different opinions on the phases, with some common points. For a deorbit mission, approaching, capturing and removal phases are the key points. Hereinbelow, these three technologies are briefly reviewed.

6.2 Approaching technologies

6.2.1 Far-range approaching

The first function a chaser has to perform, either directly after its launch or after a drifting period to be properly phased with the next target, is to perform a far- range rendezvous, typically up to 10–1 km from the debris.

This can a priori be performed using absolute navigation, which seems to be very well known and demonstrated at numerous occasions in orbit (Bonnal, Ruault, and Desjean 2013).

6.2.2 Short-range approaching

Short-range rendezvous is a key phase of chaser and target to drift close with high risk, as well, it prepares chaser to interface with target. The chaser approaches the target to a very close position depending on the method selected to deorbit the EOL satellite, and avoids collision with it.

EOL satellite is an uncooperative object, which will not provide any support to chaser during the short-range rendezvous. This process is complex. Besides non-cooperation, (Bonnal, Ruault, and Desjean 2013) reviewed the potential tumbling movement, even when the debris is gravity gradient stabilized. This movement should be limited, typically in the range of a few degrees per second along all axis, as one can expect to have a natural damping of the movement due to Eddy currents induced in metallic objects moving in the earth magnetic field.

Additionally, chaser needs to acquire the 6-DOF (6 degree-of-freedom) motion information including the position, attitude, linear and angular velocities of the target body; identify physical properties such as the inertia parameters (Flores-Abad et al. 2014a).

Proximity rendezvous (Flores-Abad et al. 2014a) is shown that this kind of maneuvers requires two phases. In the first phase, the LOS (line-of-sight) rotation is driven to zero while aligning the capturing mechanisms of the two vehicles. During the second phase, the chase vehicle maintains the angular velocity of the target and simultaneously reduces the range-to-go rate to zero. In both phases, the berthing mechanism is aligned with the LOS and the angular velocity of the vehicle relative to the LEO is kept in a small value.

Sensors are identified that they play important roles during the whole rendezvous, optical or radar; numerous possible variants are implemented to collect and calculate the necessary information, such as estimation of dynamic state, geometric shape, and model parameters of an object in orbit (Flores-Abad et al. 2014a), which instruct the precise motion of chaser.

Typical technologies usable for short-range rendezvous between chaser and debris (Figure 10) are summarized by MDA under CNES (Bonnal, Ruault, and Desjean 2013). And it should be emphasized that no single technology can complete the entire function. A significant effort in terms of Research and Technology, then in demonstration, is most probably required.

Figure 10 Typical technologies usable for short-range rendezvous between Chaser and Debris

Appendix H shows the status of significant approaching technologies.

6.3 Capturing technologies

(Shan, Guo, and Gill 2016) reviewed the capturing technologies and gave comments. Capturing phase plays a crucial role in the entire mission process. Conceptually, many methods for space object capturing have been proposed. According to their characteristics, the methods are divided into two main categories: contact and contactless capturing methods (Figure 11). Literally, the contact-capturing method is the mainstream. Because contactless-capturing methods are primarily considered for asteroid orbit deflection, only contact capturing method can be used to deorbit satellites. The contactless-capturing technologies are not discussed in this article. The most promising and significant capturing technologies are presented in Appendix I.

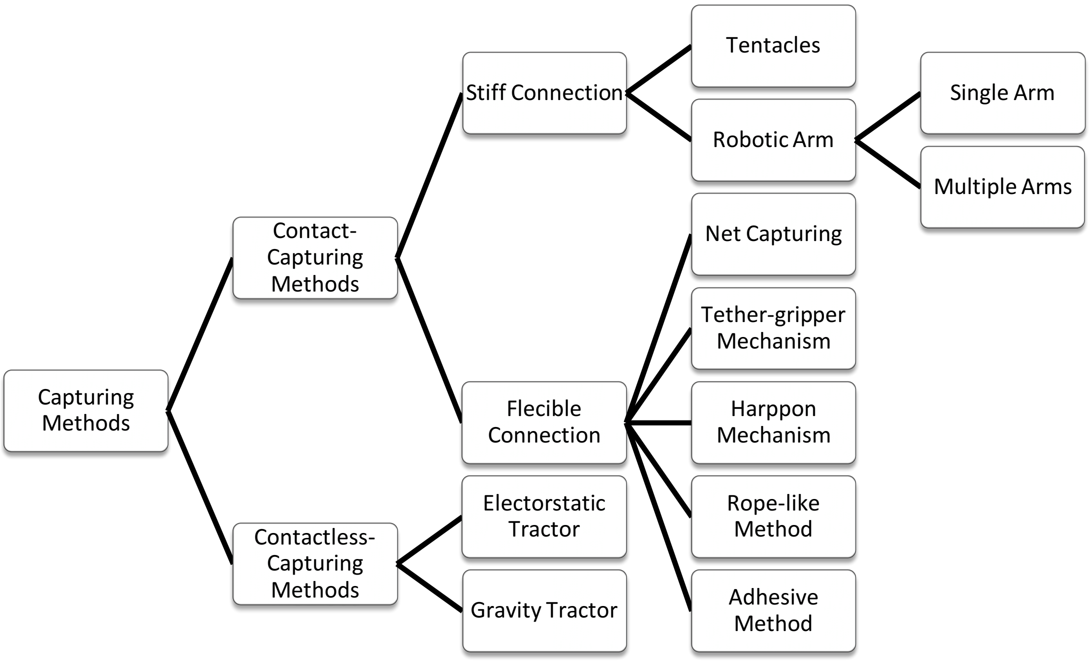

Figure 11 Concept diagram of capturing methods.

Table 11 lists the most relevant and investigated capturing technologies and their advantages and drawbacks. A comparison is drawn in this table.

Table 11 Overview of relevant capturing techniques.

Capturing methods	Advantages	Drawbacks	Examples	Institute/Sources
Tentacles	1. Stiff composite; 2. Easy to test on ground; 3. Higher Technology Readiness Level(TRL)	1. Complicated rendezvous phase; 2. Possible to be bounced; 3. Accurate relative positioning and velocity needed.	e.Deorbit CADET TAKO	ESA Aviospace Japan
Single robotic arm	1.Stiff composite 2. Easy to test on ground; 3. Higher TRL	1. Higher probability of collision; 2. Grappling point required; 3. Rendezvous and docking needed.	DEOS EPOS FREND Aolong-1	DLR DLR DARPA CALT
Multiple arms	1. Stiff composite 2. Easy to test on ground; 3. Flexible capturing	1. Complex control system; 2. Higher mass and cost; 3. Rendezvous needed.	ATLAS	UK
Net capturing	1. Allows a large capturing distance; 2. Reduced requirements on precision; 3. Compatible for different size of debris.	1. Hard to control; 2. Risk of critical oscillations; 3. Hard to test on ground.	ROGER e.Deorbit D-CoNe REDCROC RemoveDEBRIS	ESA ESA Italy Colorado Surry/Airbus
Tether gripper	1. Allows a large capturing distance; 2. Short capture operation time; 3. Lower mass and cost.	1. Difficult to test on ground; 2. Grappling point required; 3. Lower reliability.	ROGER TSR	ESA China
Harpoon	1. No grappling point; 2. Allows a stand-off distance to target; 3. Compatible with different targets. 4. multi harpoons on one spacecraft 5. Simple, highly reliable and low risk 6. High firing speed is compatible with high target spin rates	1. Risk of generating fragments; 2. Risk of breakup 3. Flexible connection, difficult to predict the movement of a target.	RemoveDEBRIS e.Deorbit Cleanspace	Surry/Airbus ESA/Airbus ESA/Airbus

6.4 Removing technologies

(Shan, Guo, and Gill 2016) also reviewed the removing technologies. Even though capturing is important, removing is more important than other phases, because some concepts don’t involve capturing phase. Similarly, the technologies are divided into three main categories according to their characteristics: propulsion, space environment based and non-space environment based (Figure 12). Propulsion is some non-space environment based technology, but it is categorized as an independent class in this article because it has a long history and that other technologies are quite novel. All the removing technologies are presented in Appendix J.

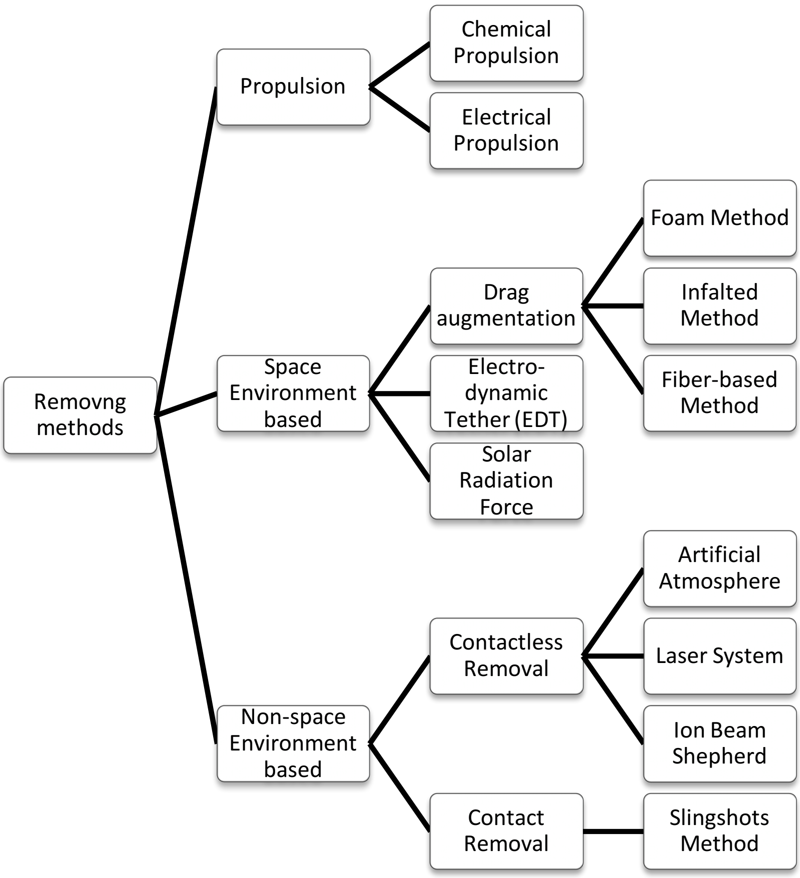

Figure 12 Concept diagram of removal methods.

Table 12 lists the most relevant removing techniques and their advantages and drawbacks. A comparison is drawn in this table.

Table 12 Overview of relevant removal techniques.

Removing methods	**Advantages**	**Drawbacks**	**Examples**	**Institute/ Sources**
Chemical propulsion	1. Short mission time 2. High TRL	1. Very High cost	Most satellites are using chemical propulsion system	/
Electrical propulsion	1. Low propellant mass requirements 2. High TRL	1. Long mission time 2. High cost	ABS–3A GOCE	Boeing ESA
Drag augmentation system	1. Allows a large distance 2. Compatible with different size of debris	1. Risk of breakup 2. Less efficient	Foam Inflated Fiber-based	ESA GAC US-Patent
Electro-dynamic tether	1. No need for propulsion system 2. High TRL	1. Capture needed 2. Unavailable in GEO	EDT	JAXA
Contactless removal	1. Allows a long distance 2. Compatible with different sizes of debris	1. Less efficient 2. Unavailable in GEO	Artificial atmosphere Laser system Ion beam shepherd	US Patent LODR ESA
Contact removal	1. Multiple targets removed 2. Short working period	1. Rendezvous needed 2. Complex control system	Slingshots	USA

6.5 Evaluation of technology readiness level

6.5.1 Estimation of TRL for approaching

Based on facts gathered in previous parts, Table 13 gives the result of TRL for approaching technologies. Currently, each technology has its own advantages and disadvantages. As mentioned before, no single method can finish the task. Therefore, different combinations of technologies are used according to different purposes to do the best performance, meaning that the TRL is high enough for real mission. For a deorbiting system, the hybrid of technologies need to be matured in the future.

Table 13 results of TRL for approaching technologies

Approaching methods	Estimate of TRL	Remark
Passive Camera (monocular)	8	Implemented in space activities
Stereo Camera	5	Tested in space activity
Laser Range Finder	6	Be used for real time scanning
Scanning LIDAR	3	Experimental stage
Flash LIDAR	3	Experimental stage

6.5.2 Estimation of TRL for capturing

Table 14 gives the results of TRL for capturing technologies. Currently, single robotic arm holds the highest position. But, harpoon and net capturing are increasing their TRLs.

Table 14 results of TRL for capturing technologies

Capturing methods	Estimate of TRL	Remark
Tentacles	3	easy to mature
Single robotic arm	8	Orbital Express, Aolong-1
Multiple arms	3	easy to mature
Net capturing	4	(Gołębiowski et al. 2016)
Tether gripper	3	
Harpoon	5	Will be 6 in 2017
Adhesive	4	

6.5.3 Estimation of TRL for removing

Table 15 gives the results of TRL for removing technologies. Currently, propulsion has the highest TRL level. But, tether technology is tested on-orbit, which means the TRL is high enough to be applied in real mission.

Table 15 results of TRL for removing technologies

Removing methods	Sub-methods	Estimate of TRL	Remark
propulsion	Electronic propulsion	9	
	Chemical propulsion	9	
Drag augmentation system	Foam	2	Materials under discussion
	Inflated	2	
	Fibber-based	2	
Electro-dynamic tether	-	8	KITE[11]
Solar Radiation Force	-	7	Not for deorbiting purpose
Contactless removal	Artificial Atmosphere	2	
	Laser System	4	
	Ion Beam Shepherd	2	
Contact removal	Slingshots Method	2	

6.6 Conclusion

The technologies related with deorbiting satellite are categorized into approaching, capturing and removing. These technologies differ a lot, which shows the emerging phase of solution. The TRL analysis shows that there are some technologies with high TRL but high price, and that the new concepts of technologies are still in the maturing phase. single robotic arm holds the highest position. But, harpoon and net capturing are increasing their TRLs. Propulsion is still the most mature technology, but EDT, which might be the most promising technology has been matured recently to a DRL of 8.

7 Efforts on Developing Deorbiting Technologies

7.1 Hot topics in terms of deorbiting technology

7.1.1 Hot topics in deorbiting research

The ISI Web of Knowledge is adopted as our target database. Keywords (deorbit, deorbiting, de-orbit, de-orbiting or debris removal) are used during searching in related fields like engineering aerospace, and then 1131 articles are refined. Subsequently, HistCite is used to analyse the subjects of these articles. After analysis, we got a list with keywords linking to the deorbiting technology (see Table 16).

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[11] http://www.ard.jaxa.jp/eng/research/kite/kite.html
http://www.npr.org/sections/thetwo-way/2016/12/09/505020386/japan-sends-long-electric-whip-into-orbit-to-tame-space-junk

Table 16. Result of bibliometrics analysis on “deorbiting”

#	Keywords	Records
1	TETHER	191
2	LASER	56
3	PROPULSION	52
4	SOLAR SAIL	36
5	ROBOT	23
Grand Total		358

7.1.2 Comments on hot topics

Tether based solution for deorbiting is grabbing a lot of attention from academic circles. It indicates that tether is a potential candidate for deorbiting, which may have some competitive advantages. According to a research (Levin, Pearson, and Carroll 2012), the tether is the only candidate that can be very economic and lightweight. The mission could cost around $400/kg on average by using tether technology. Laser technology is using for deorbiting small space debris without any capability to deorbit large objects. Propulsion technology and robot technology are so expensive that they have no chance to be economical. Solar sail is still facing some theoretical issue to be applied. To make a business feasible, the price is as important as TRL. That’s why some promising technologies like tether are prevailing others in terms of research and development.

7.2 Country examples of technological projects

Countries that have a major presence in space activity, have taken it upon themselves to develop their own technologies to successfully deorbit operational and non-operational satellites. Governments around the world recognize the problem but are being slow to act. Examples below illustrate the above-mentioned technologies from countries, to show their efforts on technological evolution without interest on commercial deorbiting services.

7.2.1 Aolong – 1 Project

The Aolong-1 (Figure 13) or ‘Roaming Dragon’ is a technological example illustrating the functionality and success of deorbiting satellites using a robotic arm (TRL: 8).

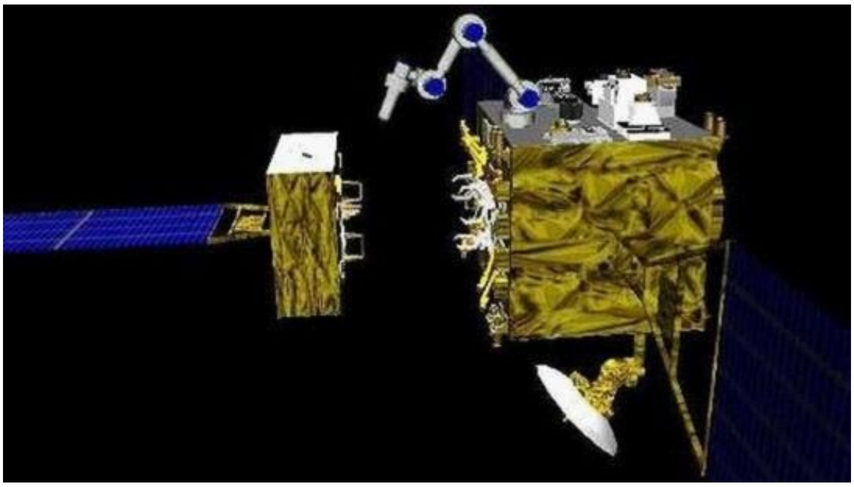

Figure 13 Aolong – 1

It was launched, aboard the Long March 7 Rocket, from Hainan, China, in 2016. It was developed by the China Aerospace Science and Technology Corporation, which is the main contractor for the Chinese Space program. This satellite is equipped with a robotic arm to grapple other satellites for deorbiting and retrieving satellites and small debris.

The Aolong-1 satellite would attempt to engage with a piece of debris by identifying target debris and approaching. But this is not as simple as it sounds; the process of approaching the target and achieving a fixed grip with a robotic arm is quite challenging as the target is constantly moving. After grabbing pieces of debris, it assists in the re-entry to a safe location, like parts of the Ocean.

7.2.2 Kounotori integrated tether experiment (KITE)

KITE is an example of electrodynamic tether (EDT), which is a promising candidate to deorbit the debris objects at low cost (TRL: 8).

JAXA performed the (KITE) project to establish and demonstrate EDT technology and to obtain some EDT characteristics, such as tether deployment dynamics, and electron emission and collection in space plasma.

JAXA took the first step to spearhead efforts towards space debris removal by conducting KITE to demonstrate the deployment of the tether and current drive through the tether. The project helps identify the features and key technologies necessary to design and develop an EDT system as a method for improving space safety by removing large debris.

The mission of the Japanese Space Agency, is to demonstrate and prove that tether technology could be used in the future to deorbit satellites.

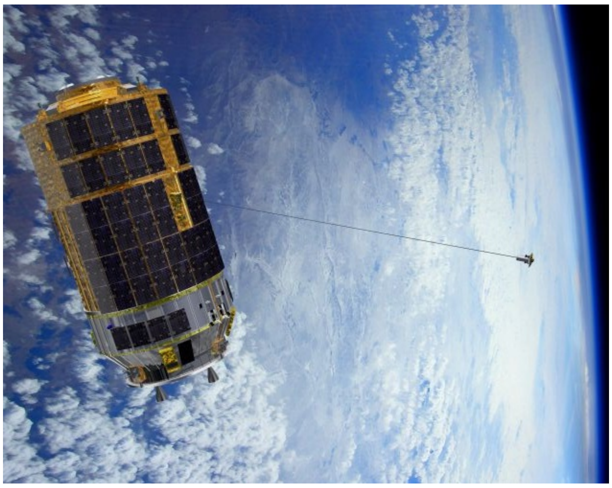

Figure 14 Kounotori 6 approaching the ISS

7.2.3 Robotic servicing vehicle from Space Systems Loral (SSL)

The United States Defense Advanced Research Projects Agency (DARPA) is working in partnership with SSL to launch in 2020 a robotic servicing vehicle (Figure 15) which will prolong the life of satellites in LEO, which also provides a deorbiting function. The spacecraft will use robotic technology (TRL: 8) to grip, refuel and move a US satellite.

SSL will work in partnership with NASA to develop the spacecraft. This will be an opportunity for the US, to position themselves in the race of satellite deorbiting and servicing.

Figure 15 Robotic Servicing Vehicle

7.3 Conclusion

The analysis shows the different preferences from academic circles and industries in different countries. The hot topics in academic circles are tether, laser and others. The tethers are argued as the most promising technology to lower the cost of deorbiting system to a level of $400/kg on average, which might be the reason why tether is the most popular technologies.

The efforts from different countries shows that there is no technology convergence in this field.

8 Feasibility Analysis

After analyzing the demand side and supply side of the commercial deorbiting market. The reality is that there is no actual market for commercial deorbiting service now. The reason is that the supply can't meet the requirements of the demand (for some customers with high maturity like ESA, the TRL of new technologies like harpoon is not high enough or the price of traditional technologies like robotic arms and chemical propulsion are too high), and that the DRLs of other potential customers are quite low to find a real market.

All in all, the TRL, DRL and the price are the key elements of success in this potential market. The following feasibility analysis will focus on DRL, TRL and price to try to clarify the market potential of commercial deorbiting services.

8.1 Analysis of DRL and TRL

For the beginning of DRL concept, DRL is deemed as an equilibrium tool for the hybridization between technology push and demand pull approaches (Paun 2011). The balance between DRL and TRL is a vital part of an innovation activity. According to some research, the balance between demand-pull policies and technology-push policies has strongly shifted towards demand-pull in recent years (Hoppmann 2015). Demand-pull policies spur investments in both production and long-term R&D, but bear the risk of a lock-in to more mature technologies (Hoppmann et al. 2013).

The status of the deorbiting market shows that some space agencies, who are potential customers, put resources on maturing dedicated deorbiting technologies, which is a typical demand-pull approach. It is clear that the current model in commercial deorbiting market is dominated by demand-pull. Later for other potential customers, it might be a hybrid of demand-pull and technology-push. The following analysis will be based on this assumption.

The rule for choosing innovation project is to invest in projects which match at the DRL+TRL>9. According to the development of technologies, the maturity of technologies will be high enough in the future. Thus, discussing technologies is not the urgent for this market. Meanwhile, maturing potential customers are the key factors for commercial deorbiting services.

From all the analysis above, the approaches for maturing commercial deorbiting markets are clear. To illustrate the approaches, Table 17 shows the synthesis of DRLs and TRLs in the deorbiting market and gives a future anticipation for DRLs. As discussed in Table 9, the anticipation of DRL for each potential customer is based on the potential external drivers and their probabilities.

Government Space Agencies

The demands from pioneering space agencies (only ESA now) are quite limited (innovators phase in the diffusion of innovation model), which leaves almost no chance for new entrants and the market capacity is not big enough to support dedicated commercial companies. The active approaches should be adopted to mature the market. For space agencies (as innovators in the diffusion of innovation model), the most important approach is providing mature technological solutions with low cost. This is the only way to capture their attention. If a supplier can't provide a solution with high maturity, the only way is to provide a clear prospect of low cost.

Mass constellation Owners

For potential lead users, the DRL of mass constellation owners are quite low (DRL=1, means that they have no interest of purchasing a commercial service to meet their concerns). To mature this segment, two approaches from different directions can be implemented. The first approach is to put efforts to expose the economic drivers of deorbiting services to those owners, and make them realize that deorbiting services will lower the risks of collision and relieve orbital resources. This can at least lower the insurance cost, save the operational fuel cost and ensure the safety of space assets. The second one is use mature solutions, demonstrations, even successful cases to leverage the potential needs. Apparently, the former approach is demand-pull and the later one is technology-push. As for other potential customers like other government users, the approach is a hybrid of demand-pull and technology-push, which means putting efforts on both side. As drivers discussed in the DRL part, the key driver for other space agencies is political pressure from antecedent space agencies. The demand will become mature if there are simultaneously enough pressure and sufficient supply of technological solutions.

Other Government Space Agencies

As discussed in Table 9, the drivers for them is not easy to influence. Political and legal drivers are mainly driven by governments themselves. The only thing that service providers can do is lowering the price.

Other satellite owners

Other satellite owners are not easy to mature, but their awareness of commercial deorbiting service can be influenced by the public opinion environment of space sector. Their anticipated DRL will be a little bit higher in the foreseeable future.

Other potential customers

Other potential customers will keep at the same DRL. The barriers for them to become actual customers is unbridgeable in foreseeable future.

Table 17 the synthesis of DRLs and TRLs in deorbiting market

Future anticipation (10 years later)	Current customers	DRL	TRL	Approaching	capturing	Removing
Other government Owners NGOs	Other government Owners Other satellite owners NGOs	0				
	Mass constellation Owners	1				
UN COPUOS	UN COPUOS	2	9			Electronic propulsion Chemical propulsion
Space Debris Community	Other Government Space Agencies Space Debris Community	3	8	Passive Camera	Single robotic arm	Electro-dynamic tether
Other satellite owners		4	7			Solar Radiation Force
		5	6	Laser Range Finder		
		6	5	Stereo Camera	Harpoon	
Other Government Space Agencies Mass constellation Owners	Government Space Agencies (ESA)	7	4		Net capturing Adhesive	Laser System
		8	3	Scanning LIDAR Flash LIDAR	Tentacles Multiple arms Tether gripper	
Government Space Agencies (ESA)		9	2			Artificial Atmosphere Ion Beam Shepherd Slingshots Method Foam/Inflated/Fiber-based
			1			

8.2 Price analysis

According to the analysis in supply-side, it is quite clear that the combination of robotic arm and chemical propulsion is generally mature enough to design a deorbiting system. But the price of such a system prevents it from being materialized, which means price itself is not only a competitive factor but also a key enabler for deorbiting services. The ESA's effort in deorbiting service is mainly focusing on maturing the potential low cost solution (e.g. harpoon and net). The reason electrodynamic tether is prevailing is due to its potential low system cost. In this part, the current cost for deorbiting service will be discussed and a pricing strategy will be suggested.

8.2.1 Current price estimation

As a key factor for a commercial service, estimations of cost are emphasized in some researches. Scientist from Agenzia Spaziale Italiana (ASI, Italian space agency) estimated costs for three different solutions (Covello 2012). In the estimation, they chose three different Concepts of operations, which are Revolver-TDK-CP[12], Revolver-EDT-CP[13], and Phoenix-EP[14]. To lower the single mission cost, the cost for deorbiting 140 objects in 28 years is chosen as the estimation target. The cost of satellite for the three concepts has been estimated considering the Cost Estimating Relationship derived in the Unmanned Space Vehicle Cost Model 8th edition. The cost of launching services and operations are considered in the estimation. The result shows that the costs for three concepts are from $ 1144 million to $ 1289 million (details in Table 18). Cost for deorbiting one object is about $ 9 million, which is not a huge amount, compared with the value of a large satellite (which is around $ 100 million).

Table 18 estimations for deorbiting 140 objects in 28 years for 3 solutions

Concepts of operations	Total recurrent [M$]	Annual operation costs [M$]	Operations costs 28 yrs [M$]	Total [M$]
Revolver-TDK-CP	1060	7	196	1255
Revolver-EDT-CP	1094	7	196	1289
Phoenix-EP	752	14	392	1144

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[12] In the Revolver concept the de-orbiting is performed attaching to the debris a device that will provide the necessary ΔV to bring it to the selected final disposal orbit.
TDK means thruster de-orbiting kit.
CP means chemical propulsion.
In this case the following phase can be identified: 1. Transfer to the orbit of the selected debris. 2. Rendezvous with the selected debris. 3. Docking with the debris using a robotic arm. 4. Attachment of the de-orbiting device. 5. Undock of the debris. 6. Ignition or activation of the de-orbiting device.

[13] EDT means Electro Dynamic Tethers. Revolver and CP have the same meanings with Revolver-TDK-CP

[14] The Phoenix concept consists of a debris removal satellite that performs the de-orbiting of the selected debris carrying it to the selected final orbit. EP means electric propulsion.

Concerning the R&D cost, the market capacity of commercial deorbiting service is critical for lowering the total cost. But, the political issues in the space industry result in boundaries between major space-faring countries, which fragmentize the global market. If the market keeps steady as expected (5 large objects per years), the market capacity can’t support a mature commercial business model. The early adopters are critical in terms of lowering cost.

8.2.2 Pricing policies for new entrants in commercial deorbiting service

As mentioned above, price is a key factor for deorbiting service. On the one hand, the pricing policy will provide competitiveness for contracts. On the other hand, pricing will mature customers’ demand as high TRL.

Price is a key factor for start-ups in commercial space industry. SpaceX’ success is based on the anticipation of much lower prices for launching service. OneWeb’s pricing strategy makes it possible to gain interest from investors.

All in all, the pricing policies can enable a new entrant to be funded, invested, or even to become a contractor in the near term.

8.3 Conclusion

The analysis shows that DRL, TRL and price are critical for commercial deorbiting services. As for the commercialization of innovation, deorbiting market is currently a demand-pull one. To mature this industry, the hybrid of demand-pull and technology-push need to be taken into consideration. The strategies for different potential customers need to be customized. It is feasible to have a market of several kinds of potential customers. The price for deorbiting a satellite by using sole supplier is as low as $ 9 million, but it is not low enough. The pricing policy for new entrants is critical in terms of fundraising and investment attraction and competition for contracts.

9 Case study - ESA's Efforts on Deorbiting Envisat

9.1 Envisat background

Envisat (Figure 16) which was launched by ESA in 2002, is a nine meter long, 26-meter cross section, 8,000kg satellite. It was launched to monitor Earth’s oceans, atmosphere, land and ice caps using a set of 10 sophisticated sensors. ESA lost contact with the satellite in 2012, declaring an end to the satellite’s mission. Space debris has attracted much attention and interest in the past years, which has made this non-functional large satellite in low earth orbit, an important one to deorbit.


Figure 16 Envisat Satellite

A recently-published paper from physics students at the University of Leicester explores the possibility that Envisat could be the catalyst that sets off a chain of events much like those depicted in the Academy Award-nominated film ‘Gravity’. According to the study, Envisat currently orbits at an altitude of roughly 790 km, which happens to be the region where the amount of space debris surrounding the planet is the greatest, so deorbiting Envisat is certainly worth considering.

Reviewed in the *Journal of Physics Special Topics*, run by the University’s Department of Physics and Astronomy, the students claim that Envisat could pose a serious collision risk due to its size and current orbit altitude. Furthermore, they note that it might be too costly and complicated to bring the probe back to Earth.

9.2 Stakeholders

The European market and delegation are stakeholders in this case. ESA being the primary one, at innovator level. Other satellite owners in the similar orbit can be a significant stakeholder, as their assets are under risks. Other stakeholders such as the media and other countries such space agencies may influence and affect the mission.

9.3 External factors influencing the case

9.3.1 Legal issues

Experts at ESA think that any collision with Envisat could happen, and could create an enormous cloud of space debris and trigger a cascade of following impacts with other satellites, space stations and basically start the "Kessler Syndrome". They are therefore faced with the choice of either removing Envisat from LEO or risk being held liable if their satellite damages another orbital body.

According to a member of the Institute Space of Law (ISL), since ESA chose to continue operating Envisat until it had too little fuel to be powered to a lower orbit, as international guidelines prescribe, ESA could be held liable for negligence, or even gross negligence, if Envisat or pieces of it damage an active satellite in the 100-plus years Envisat will remain in orbit, according to the IISL analysis.

“Why did ESA prioritize the operating of Envisat until the last drop of fuel rather than the stability of this precious area in outer space, and the welfare of this valuable orbit?” Mejia-Kaiser said in her presentation. While Envisat was launched before orbital-disposal guidelines were published, the decision to continue operating it was made well after ESA signed a code of conduct that adopts these guidelines.

9.3.2 Environmental issues

It is not possible to maneuver Envisat as it has lost contact with the ESA. It is expected to remain in space for about 150 years, meaning that there is a chance that it will collide with other satellites or space junk.

In a presentation in Naples, Italy, to the 63rd International Astronautical Congress, Martha Mejia-Kaiser, an IISL member from the Autonomous National University of Mexico, said Envisat is a “ticking bomb” that poses an unusually large danger to a heavily populated corridor in polar orbit at 780 km in altitude. Adding to the danger of this satellite, is the residual gases, propellant remnants, still charged batteries and other stored energy.

This would not only hinder the ability of future space missions, which would need to make it through the region of densely populated debris, it could also lead to damage to other key satellites and spacecraft that are in orbit.

9.4 Analysis of ESA’s demand

According to ESA’s clear demand of commercial deorbiting service, its DRL to deorbit EnviSat is high, which is 7 as mentioned earlier.

9.5 ESA's efforts on deorbiting technologies

ESA is going to adopt propulsion system to deorbit EnviSat. The main efforts for ESA is focusing on the capturing technologies. For ESA, other space agencies are studying future debris-removal technologies that today are viewed as overly risky and expensive.

To minimize the risk involved with the mission, a few capture mechanisms are being investigated (Table 19). ESA put resources mainly on the harpoon and nets. The maturities of these technologies are growing a lot during the past year. Appendix K details the projects lead by ESA to mature commercial deorbiting service.

Table 19 Capturing technologies invested by ESA

#	Technologies	TRL
1	Robotic arm	8
2	Tether gripper	2
3	Throw nets	4
4	Harpoon	5
5	Clamping mechanism	3
6	Robotic arm + Clamping tentacles	2

9.6 Feasibility of deorbiting EnviSat by commercial service

The efforts made by ESA show the high DRL of ESA, and the steady progress of TRL of related technologies. The technology options are gradually focusing on some technologies like harpoons and net, which have a characteristic of low cost. The DRL, TRL and potential low cost, which are the key success factors, determine the feasibility for ESA to purchase a commercial deorbiting service in the near future.

9.7 Conclusion

In areas where space debris is dense, large objects in this region poses a major threat to the debris population (N. L. Johnson 2008). To stabilize the growth of debris in LEO, simulations have been performed and indicate that 5 large objects in LEO would have to be removed annually (Liou 2011) (N. L. Johnson 2008). Hence, the removal of one the largest non-functional satellite's in LEO is of interest to ESA; as it would keep the orbit safe, ensure the survival aspect of the orbital missions, protect people on Earth and ensure that there are no collisions in space.

10 Overall Conclusions and Recommendations

10.1 Conclusions

The analyses above show the status of commercial deorbiting, the demands of customers, the supplies of technologies, the feasibility of commercial service.

Currently, the market is quite immature, but the market capacity is quite high. The stakeholders are identified and discussed. Then, a series of potential customers are identified. Some space agencies are innovators, whereas the owners of mass constellations are potential early adopters. Although the DRL for potential customers are more or less low, but influenced by foreseeable external factors, the probability of their emerging is high. Technologies are being matured by space agencies, but not mature enough. The DRL, TRL and price is critical for the success of commercial deorbiting service, and pricing policy is the vital factor for start-ups in this sector. The case study of ESA's efforts on deorbiting EnviSat shows the feasibility of commercial deorbiting service in a narrow market.

According to this research, commercial deorbiting service is feasible in the future, if differentiated approaches for external factors could be implemented successfully to mature the customers.

10.2 Recommendations

The recommendations are for those who have interests to provide commercial deorbiting services. As a potential business driven by innovation, the maturity of customers' demands and suppliers' solutions is the crucial factor. The efforts should be emphasized on the demand and supply simultaneously. Meanwhile, flexibility is needed, because the discussions in this research are based on current circumstances, which can change in the future.

10.2.1 Influencing the future to mature customers

Different approaches discussed in feasibility analysis part. Those approaches are only options for stakeholders. The maturity of customers' demands is the priority in commercial deorbiting market. The key fields include political factors, legal factors and economic factors, according to the discussion above.

10.2.2 Investing in technologies to take advantages

The key words for technological solution is low cost, which enables a competitiveness. Technologies can't be ignored in innovation business program.

10.2.3 Appropriate pricing policy

The only reason for the absence of commercial deorbiting contract is price. All the efforts for developing new technologies are focusing on simplicity to lower the cost. An appropriate pricing policy can be attractive for investors and potential customers. For new entrants without enough investment, it can also enable them to be approached by capital.

10.2.4 Being aware of market drivers

Market drivers are essential for this sector. The potential external factors discussed in former parts can’t cover everything. The probabilities of some factors are categorized as low or very low, which doesn’t mean it can’t happen. Being sensitive with all the probabilities is the key in catching fleeting opportunities and minimize the risks.

Appendix A: Interviewees

Interviewee	Title	Length of interview	Main Topics
Laurent Arzel	Delegate of AMBA FT18, TBS (Former Senior Associate, PWC)	1 Hour (face to face)	General information of Space industry, stakeholders, EnviSat, deorbits.
Romain Lucken	Ph. D students from Plasma physic laboratory in Paris	1 Hour (cellphone)	Business model for de-obit, Technology, cost level, driven factors for de-orbit
Andrea Harrington	PhD in Space Governance at McGill University Institute of Air and Space Law	1 Hour (cellphone)	International law/regulation on Space. What's the future of space law regarding LEO satellites? What happens in the case of a collision?
Chris Kinstadter	XL Catlin (3rd insurance firm for the aerospace sector)	1 Hour (cellphone)	Insurance in Aerospace industry
Olga Rosanova	TBS research assistant	1 Hour (cellphone)	Cost analysis of deorbiting
Cédric BALTY	VP Innovation and Marketing, Thalès Alenia Space	1 Hour (cellphone)	Commercial opportunity of de-orbit EOL satellites, TRL, driven factor, opportunity for commercial deorbiting start ups
Bruno Bajard	Marsh Insurance	1 Hour (cellphone)	Insurance in Aerospace industry
Thierry Colliot	Head of Space at AGCS	-	No response
Joe Anderson	Orbital ATK Director, Mission Extension Vehicule services	-	No response
Morris Jones	Space Analyst	Written	Aolong 1
Damien Cailliau	Strategy, development and organisation consulting for industrial SMEs, Pepper Road	-	No response

Appendix B: Main phases of the project

Main phases of the project	Phase based on time	Content
Understanding the topic	20-Nov-2016 to 5-Dec-2016	MCTP team had several round discussion based on proposed information, till met with supervisor to decide the research direction.
Identify different dimensions	21-Nov-2016 to 12-Dec-2016	After discussion and rough research on the topic, we identified the main dimensions included in our research, such as stakeholders, segmentation, legislation, political and technology etc.
Make decision of the main tools and main methodology	23-Jan-2017 to 20-Mar-2017	After MCTP meeting, the draft of structure was proposed to launch the discussion on tools. As courses going, more tools were presented to us to be added into our research. With the final version of structure, we confirmed our all tools and methodology.
Gathering information	21-Nov-2016 to 20-Mar-2017	MCTP team collected relative information from primary source and secondary source, which were shared by team to finalize the paper.
Interview	5-Dec-2016 to 20-Mar-2017	Due to lack of information on demand, we need to interview some experts to collect more information. We selected proper interviewees and conducted the interview via cellphone by small groups.
Individual work	21-Nov-2016 to 17-Apr-2017	It included the phase of gathering information, and researching on responsible dimension separately.
Synthesizing phase	3-Apr-2017 to 22-Apr-2017	Draft of individual work is ready to be synthesized. Then responsible revised the relative part according to comment during discussion.

Appendix C: Position of political actors and regulators

Europe has made public its last European Space Policy in late 2016. As explained in the communication addressed to the European Parliament, the European Commission notably seeks to *"reinforce Europe's autonomy in accessing and using space in a secure and safe environment", "strengthen Europe's role as a global actor and promote international cooperation", and "ensure the protection and resilience of critical European space infrastructure".* The Commission notably declares that *(...) space is becoming a more contested and challenged environment. New competitors - both public and private - are emerging around the world, partly spurred by the reduced costs of developing and launching satellites. Growing threats are also emerging in space: from space debris to cyber threats or the impact of space weather". (...)The EU should lead the way in addressing the challenges posed by the multiplication of space actors, space objects and debris in line with the UN conventions related to space. (...)The proliferation of space debris remains the most serious risk to the sustainability of space activities and will continue to be addressed at European and international level*[15]*".*

The political awareness concerning satellites and debris mitigation, though relative, is quite recent. It led to several regulations which are the fruit of political and legal national and international discussion that must be mentioned here.

The National American Space Agency, NASA, is the first to have established orbital debris mitigation guidelines in the 1990's[16]. In 1994, the Committee on the Peaceful Uses of Outer Space, and notably its Scientific and Technical Subcommittee, "considered, for the first time, on a priority basis, matters associated with space debris under a new item of its agenda[17]".

NASA's debris mitigation guidelines were finally published in 1995. For the first time, they limited the long-term presence of LEO and upper stage spacecrafts to 25 years in order to protect the space environment. They also stated that "*if a random reentry results in a human casualty risk greater than 1 in 10,000, then a controlled reentry must be conducted to ensure the risk is below the acceptable threshold*".

These guidelines have been accepted by the US, who published in 2001, on NASA's and DoD's recommendations, the U.S. Government Orbital Debris Mitigation Standard Practices.

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[15] European Commission's communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. October 27th, 2016. "Space Strategy for Europe". Brussels. https://lc.cx/Uruu

[16] In 1993 and 1995, NASA produced two detailed debris mitigation guidelines: "NASA Management Instruction (NMI) "Policy for Limiting Orbital Debris Generation" (1993) and "NASA Safety Standard (NSS) 1740.14 "Guidelines and Assessment Procedures for Limiting Orbital Debris" (1995). Source : Liou, J, and David Jarkey. 2015. "Orbital Debris Mitigation Policy and Unique Challenges for Small Satellites," n°. August.

[17] UN Office for Outer Space Affairs. 2010. "*Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*".

In 2002, the Inter-Agency Space Debris Coordination Committee reached a consensus that led to the publication of international orbital debris mitigation guidelines that were submitted to and recognised by the United Nations.

In late 2007, after several of working groups' negotiations, the UN Committee on the Peaceful Uses of Outer Space eventually endorsed its own Space Debris Mitigation guidelines, inviting "*Member States to implement those guidelines through relevant national mechanisms*[18]". Though "*legally non-binding under international law*", these guidelines are supposed to represent an international legitimate consensus on the topic, a political and "*moral force*" as the Space legalist Andrea Harrington explained in the interview led on the 16th of February 2017.

A year before the UN guidelines' publication, in 2006, the US government cited NASA's guidelines in its national space policy (pursued in its 2010 version). Many foreign space agencies and international bodies followed this path: France, Austria, the Netherlands, and the United Kingdom also have space debris mitigation guidelines, as well as Russia, China, Japan and the European Space Agency.

Despite such an institutional and official consensus, the practical implications of space debris mitigation, to which deorbiting actions could belong among other on-orbit servicing activities, divide nations and lead to a political and strategic dialectic.

A mock hearing organized by the On-Orbit Servicing Working Group of the Canadian Space Generation Advisory Council in 2014 in the frame of the 2014 Toronto Space Generation Congress, tends to demonstrate it. Led in support to the United Nations Program on Space Applications, this mock hearing, structured around the participation of 26 international stakeholders, aimed at gaining "accurate perspective of stakeholders" regarding what could "On-Orbit Servicing and Active Debris Removal (…) offer the satellite industry, as well as potential disadvantages for international relations between space faring nations".

On one hand, "domestic military liaisons", i.e "highly ranked military officials with responsibility in classified reconnaissance and Earth observation areas", are concerned with "the potential hostile capabilities of servicing modules" in a "space weaponisation" logic. A view that seems to be shared by "non-allied country delegations (and their) military attachés", who are "mainly concerned about the possible hostile capabilities of OOS units and potential interference with spy satellites". On the other hand, "allied country delegations" seem in favour of licencing and regulating on-orbit servicing with view to mitigate space debris[19].

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[18] UN Office for Outer Space Affairs. 2010. "*Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*".

[19] Space Generation Advisory Council. 2014. "On-orbit servicing commercial opportunities with security implications". *Space Generation Congress*. Toronto.

Appendix D: Operators and manufacturers' perspectives

As described by Stefano Antonetti, D-Orbit Program Manager in a 2015 research paper, "*the implementation of dedicated Space Debris Mitigation technologies is still seen by many operators and officials as a burden for space industry's competitiveness*[20]", in LEO just like in GEO. This occurs despite the official debris mitigation guidelines released by the IADC, the UN, and some national legal acts.

Their concerns and reluctance take on different dimensions.

- LEO has the highest debris collision hazard, as highlighted by Schaub[21]. Indeed, LEO has an annual probability of collision exceeding 0.8% for 10m2 satellite colliding with a 1 cm debris or larger. Operators keep in mind that malfunctions related to debris are relatively rare in LEO.
- The direct and indirect perceived costs associated with deorbiting mitigation devices, whom Ellery, Kreisel and Sommer offer an interesting insight[22]: "Direct costs such as propellant consumption for collision avoidance manoeuvres, downtime during the latter manoeuvres, insurance costs and decommissioning at the end of mission are paired with costs of other nature: the risk of failure on the decommissioning phase, and thus, the cost of a constellation (that) may suffer having a dead satellite in the proximity of operative satellites, (as well as) the reputational loss (…)".
- Uncertainty regarding the economic value and direct benefits withdrawn from deorbiting services. More than a thousand of satellites will be launched in LEO in the next years along with the amplification of new constellations. Their business models lie upon a large amount of similar low-cost satellites backed up with redundant ones. As underlined by Adilov and al. in their research study, it is indeed more competitive for commercial operators to have more operational assets than necessary. They also highlight that international mitigation guidelines "impose direct costs [to space debris mitigation] but confer only indirect benefits on operators, which lead to the conclusion that "marginal costs of compliance will exceed marginal benefits[23]". For this reason, operators, especially those of "low-risk assets with short mission lifetimes[24]", express doubts regarding deorbiting servicing.

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[20] Antonetti, Stefano. 2015. "Contributing to orbital sustainability with an independent decommissioning device for satellite and launcher space implementing space debris mitigation measures". *5th Challenges in European Aerospace, Air and Space Conference*.

[21] Schaub, Hanspeter, Lee E Z Jasper, Paul V. Anderson, and Darren S. McKnight. 2015. "Cost and Risk Assessment for Spacecraft Operation Decisions Caused by the Space Debris Environment." *Acta Astronautica* 113 (August). Elsevier Ltd: 66–79.

[22] Ibidem.

[23] Adilov, Nodir. 2013. "Earth Orbit Debris: An Economic Model." *Available at SSRN:* https://lc.cx/JjqJ

[24] Schaub, Hanspeter, Lee E Z Jasper, Paul V. Anderson, and Darren S. McKnight. 2015. "Cost and Risk Assessment for Spacecraft

For these reasons, they tend to choose not to respond to space debris mitigation requirements and to ignore any possibility of post-mission disposal. In the frame of the abovementioned mock hearing organized in Toronto 2014 by the On-Orbit Servicing Working Group of the Canadian Space Generation Advisory Council, on-orbit servicing potential customers expressed that "*without regulation, (they) would hesitate to sign contracts for OOS missions*[25]".

In the long run, this non-action response will imply, as they are aware of, to develop dodging devices to avoid collision in LEO. A choice that could generate higher insurance premiums as the risk of orbital collision raise along the densification of LEO.

Operation Decisions Caused by the Space Debris Environment." *Acta Astronautica* 113 (August). Elsevier Ltd: 66–79.

[25] Space Generation Advisory Council. 2014. "On-orbit servicing commercial opportunities with security implications". *Space Generation Congress*. Toronto.

Appendix E: Position of insurers

According to the insurance broker Marsh Insurance, the year 2016 was deemed a good year for space insurers, with a US$400 million profit. According to the Space Insurance Market Review, released by Marsh Insurance in 2016, space insurers are perceiving important challenges with regards to the emerging satellite constellations to be deployed in LEO and GEO orbits and to the new business model imposed by Space X with its Falcon 9 reusable spacecraft. Questions are notably emerging about the way Space X's reconditioned vehicles could be assessed, and about the difficulty to evaluate the risks inherent to the new satellite constellations and their pricing factors. These questions, particularly blatant in Low Earth Orbit, were mentioned by Bruno Bajard during his interview: "*the paradoxical situation concerning these new LEO constellation projects is that they are low-cost. Their view is to launch very low cost satellites, with much less margins, redundancies, or equipment constraints. If they do that, they are likely to launch unreliable satellites up there. They are quite satisfied with it because it is highly lucrative and because they have inter-satellite redundancies. (…) Yet, they may not be in position to deorbit their satellites safely in the end. How can they be efficient and reliable enough to keep space clean? How can they achieve both objectives? I think it is going to be interesting".* From Bruno Bajard's view, space insurers tend to warmly welcome such constellations as new business perspectives. But they are also worried about the increased risks of serial losses, for the satellites are all identical. "*Experience has shown that when something goes wrong with one satellite, it is very likely to happen with the others. That's terrible for insurers, because it is like insuring against inflation or diseases. There is not enough mitigation of the risk*".

Quite interestingly, insurers seem to be more nuanced about it. While reasserting the necessity to reduce the LEO mitigation guidelines' timeline (25 years) drastically, space insurers consider LEO satellites' constellations as a good way to diversify their insured satellite portfolio. An idea reinforced by the fact the LEO satellites are currently the less insured category (Global Allianz reports that fewer than 30 LEO satellites were insured in 2011[26]). As Chris Kunstadter, Senior VP and Global Underwriting Manager Space at XL Catlin, one of the largest insurance companies in the international market, explained: "*I just spent the few days at the Satellite Conference in Washington DC, and a lot of talk was about how nobody wants to make any decision about launching new GEO satellites, because of this preparation of LEO constellations. (…) The GEO market is still there, but very flat. Operators are using LEO in addition to GEO*[27]*"*.

The evolution of space insurance premiums globally shows that they have been divided by 2 in 16 years, evolving from 1,200 US$bn in 2000 to 606 US$bn in 2016.

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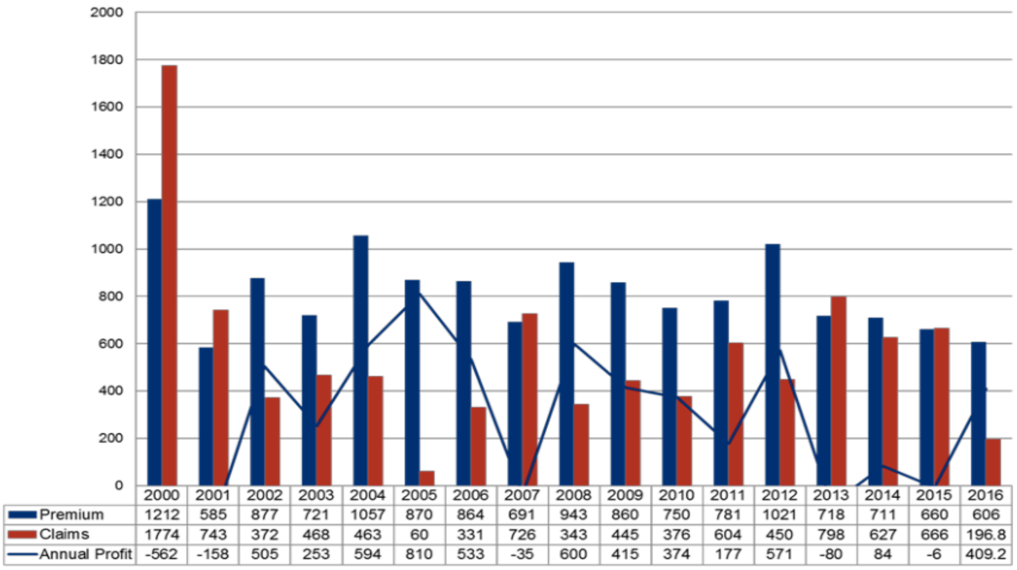
[26] Allianz Global Corporate & Specialty. 2012. "Space Risks: a new generation of challenges".

[27] Sayings withdrawn from Chris Kundstadter's recorded interview, March 10th, 2017.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Premium	1212	585	877	721	1057	870	864	691	943	860	750	781	1021	718	711	660	606
Claims	1774	743	372	468	463	60	331	726	343	445	376	604	450	798	627	666	196.8
Annual Profit	-562	-158	505	253	594	810	533	-35	600	415	374	177	571	-80	84	-6	409.2

Figure 17 Worldwide evolution of insurance premiums and claims from 2000 to 2016[28]

This demonstrates the instability of the space insurance market, mostly due to "*very uncertain times in terms of ongoing business, financing and technical developments" in the space industry*[29]". It can be easily assumed that, to reduce the risk of their global portfolios, space insurers, strategically, will facilitate the emergence of LEO constellations and rush into this market, even though, as mentioned by Chris Kundstadter, the premiums inherent to constellations are going to be lower. This can be explained by the very specific constellations' insurance business model. "*As more and more LEO constellations come along, the attitude of operators is to launch a thousand in order to have 800 working. So, they don't need to insure the individual satellites in orbit. They just need to insure them individually before and during the launch of the rocket*". This will ineluctably lead to the reduction of insurance premiums. Yet, considering the potential of the LEO market, engaging in LEO constellations' insurance would still be highly profitable.

As another insurer interviewed in this research said: "*Everyone says: let's see, the operators should pay for it, the insurers should pay for it, you know… If there is no debris remediation, we just have to take that into account in our pricing and just charge a lot more money for it. But we are not going to pay to remove those objects from their orbit, it's not our responsibility, we just react to the environment. We could probably make more money if we don't!*[30]". This is emphasized by Schaub in his research. Indeed, in the case of rockets bodies that are sometimes still covered by third party insurance from 30 days to 1 year after they accomplish their mission, insurers would face lower premium if a solution to avoid debris collision is

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[28] Marsh Insurance Report, 2016

[29] Sayings withdrawn from Chris Kundstadter's recorded interview, March 10th, 2017.

[30] Sayings withdrawn from an interview led with a space insurance representative willing to remain anonymous, March 24th, 2017.

found. Yet, as nuanced by the author, this wait-and-see attitude could rapidly change "*if there is catastrophic collision of a large, insured satellite*". Quoting Thierry Colliot, space insurer at Allianz: "*You can potentially lose the premium of a whole year in one single event*[31]". Rather, insurance companies might give more credit to on-orbit servicing, notably repairing capabilities, "*for their possibility to reduce payouts in case of failure*" (International Space University, 2007[32]).

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[31] Schaub, Hanspeter, Lee E Z Jasper, Paul V. Anderson, and Darren S. McKnight. 2015. "Cost and Risk Assessment for Spacecraft Operation Decisions Caused by the Space Debris Environment." *Acta Astronautica* 113 (August). Elsevier Ltd: 66–79.

[32] International Space University Team Project Report. 2007. "DOCTOR: Developing on-orbit servicing concepts, technology options and roadmap". *International Space University* (Summer Session Programme).

Appendix F: Environmental issues in space

Increasing number of space debris is one of the major concerns of space pollution. As of the beginning of 2016, Christophe Bonnal, Senior Expert at CNES, reports that 5,000 space launches have taken place since the beginning of space exploration. These generated a total of 41,400 artificial big size objects (beyond 10 cm). A great majority of them (23,800) have already left the circumterrestrial space, either voluntarily, like the US space shuttle or the Russian Soyouz, either through a progressive altitude decrease followed by an entry into the atmosphere. This leaves one with **17,600 space objects in orbit** (all orbits included), composed of 4,200 satellites, among which, roughly 1,100 only are still functional (as explained in the following section of this research, assessing the exact number of active satellites is quite difficult regarding the presence of confidential non-cataloged governmental and military owned satellites). Next to these "useful" satellites, one can also find 2,100 superior rocket stages, and 1,900 operational debris. Finally, close to 9,400 big fragments coming from rocket explosions, debris or meteorite collisions, are also cataloged. In total, **94 % of the cataloged orbital population is composed of space debris**[33]. The LEO orbit, which has determined the scope of this research, is particularly crowded and will be even more in the near future with the constellation effect. The most densified area can be found around 800 km of altitude. In comparison, the second pic of density, located in GTO, corresponds to 100 times less important ones than in LEO, as shown below:

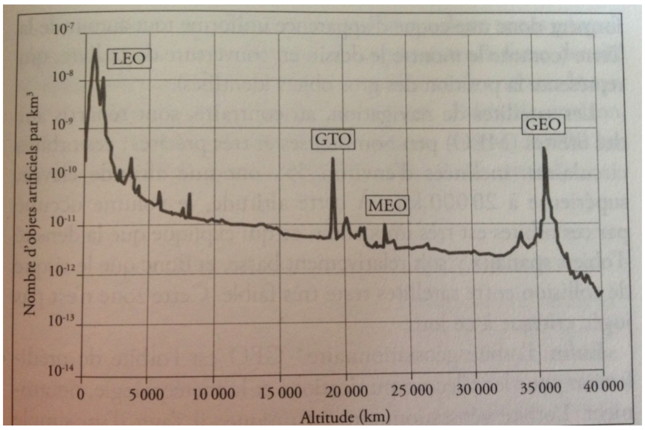

Figure 18 Number of artificial objects per km3 depending on the altitude (CNES, 2015)[34]

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[33] Bonnal, C. *Pollution spatiale, l'état d'urgence*. (Paris, Belin, 2016), 26-27.

[34] Mentioned by Christophe Bonnal, Senior Space Expert at CNES, 2016

Appendix G: Legal issue in space mitigation

1. The blurred legal frame of space delimitation.

In this regard, the absence of internationally accepted legal definitions of space orbits in international binding law is meaningful. As Andrea Harrington, Air and Space Law Instructor at McGill university, indicated: "*In fact we don't have even a definition of where aerospace ends and begins in international law, or in most domestic laws*[35]", apart from a few countries, notably Australia. Without being directly at the origin of LEO's future densification, this weakens the influence of space law and guidelines to regulate its inherent activities.

In the same way, no law, either international or national, makes any difference between a debris and a decommissioned satellite still in-orbit. The Outer Space Treaty considers them both as "space objects", vaguely described as "*objects launched in outer space*", *including "objects launched or constructed on a celestial body*". The 2006 IAA Cosmic Study on Space Traffic Management pointed out that "*no legal distinction is made between valuable active space-craft and valueless space debris*[36]". Chatterjee (2014) underlines that, beyond the fact that international space law has not yet defined accurately what a space object is, it has also been remaining silent "*as to when, if at all, a space object or its component or fragmented parts, ceases to be a space object*[37]".

Yet, prior to the redaction of the COPUOS guidelines relative to space debris mitigation, a consensual definition of space debris was elaborated by its Sciences and Technical Subcommittee as follows: "*Space debris are all manmade objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized*". This definition was toned-down by the UN COPUOS guidelines: "*All man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional*". In spite of this attempt, this definition is absent of the guidelines themselves, being only mentioned in the introductory section. Furthermore, as highlighted by Chatterjee, "*this definition is explicitly limited to the purpose of this document by a preceding proviso*[38]".

This shortage has crucial impact on the determination of liability in case of a collision in space, which could appear as a lack of legal constraint to force operators to deorbit their decommissioned satellites.

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[35] Sayings withdrawn from Andrea Harrington's recorded interview, February 16th, 2017.

[36] Contant-Jorgenson C, Lala P., & Schrogl K-U. 2006. "Report: The IAA Cosmic Study on space traffic management". 22 Space Policy 283 at 287.

[37] Chatterjee, J. 2014. "Legal issues relating to unauthorized space debris remediation". 65th International Astronautical Congress. Canada.

[38] Ibidem.

2. Complexity of the non-binding nature of international regulations.

In that matter, two difficulties inherent to this problem will be further described below.

- **First difficulty – the absence of constraining clause regarding satellite registration:**

On one hand, the Registration Convention (1974), signed by only 45 countries so far, is meant to oblige space companies to be registered and to register their space activities as well as their satellites by the State that shelters their headquarters. This registration has to be carried out in national registers as well as in UN registers. In the same way, the Outer Space Treaty (article 7) and the 1972 Liability Convention (article 2) stipulate that under International Space Law, States are internationally liable for their national public and private activities in outer space. As Pr Ram S. Jakhu indicated during an IAASS Conference on space safety in 2013, "*the requirement of international registration of space objects was adopted pursuant to a belief that a mandatory system of registering space objects would assist in their identification and would contribute to the application of international space law, particularly in determining responsibility and liability in cases of accidents*[39]". Yet, in this regard, as he pointed out further in his analysis, States tend to delay or decide not to send the required information to the UN Secretary General, notably because there is no specific time limitation for international registration.

As of the last years, and despite the moral strength of the Registration Convention, the number of UN registrations tend to slow down. As an example, the official US Registry of Space Objects Launched in Outer Space seems to have registered the US satellite Iridium 33, launched by Russia and owned and operated by Motorola (US). Yet, as it asserted after the destruction of Iridium 33, the satellite was not registered with the UN by the US. The researcher additionally indicates that as of May 22nd, 2013, date of the IAASS Conference, "*the US registry still shows that Iridium 33 satellite is in orbit, though it has been destroyed more than four years ago*" following a collision with the Russian dead satellite Cosmos. This demonstrates the relativity of space international binding laws, and reveals that there is no accurate and updated global overview of the real number of satellites in orbit today, whatever the orbit.

This is likely to trigger difficulties in their identification, notably in LEO, "*particularly if they happen to be involved in accidents in outer space or, if they survive on re-entry, on Earth causing damage*[40]".

- **Second difficulty – the non-binding nature of international space laws:**

This phenomenon is reinforced by the absence of clear, consensual and binding space traffic rules that actually makes it uneasy to enforce liability and generate legal consequences out of it. Article 9 of the Outer Space Treaty edicts that space actors should avoid "harmful

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[39] Jakhu, Ram S. 2013. "Regulation of Small & Micro Satellites". Institute of Air and Space Law, McGill University, Canada. Contribution presented in the frame of the International Space Safety Conference, Montreal (May).

[40] Ibidem.

interference" in other States' activities in outer space and should also avoid any "harmful contamination of their activities in outer space". In a more positive manner, space actors have the duty to observe "a standard of care or due diligence in performance of their activities (Chatterjee, J. 2014)[41]". Article 7 specifies the condition of application of liability: "*Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies*".

In that matter, China's test of its antisatellite weapon in 2008, that led to the destruction of its own satellite and to the creation of millions of space debris, clearly appears as a violation of article 9. Yet, no single member of the international community claimed for it and China faced no legal consequence.

In the same way, the COPUOS mitigation guidelines stipulate that space actors should "*limit the probability of accidental collision in orbit*" (…) and that, "*if available orbital data indicate a potential collision, adjustment of the launch time or an on-orbit avoidance maneuver should be considered*" (guideline n°3). Guideline n°6, on the other side, recommends to "*limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-earth orbit region after the end of their mission*": "*Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region*".

In this regard, the collision between Iridium and Cosmos demonstrates that disrespecting these guidelines, voluntarily or not, is not likely to trigger any legal consequences for states or space actors' wrongdoings. Indeed, as Armel Kerrest, Space law expert and professor at the University of Brittany explained, the Iridium satellite was actually controlled and able to manoeuver to change orbit. Iridium was aware of Cosmos 2251's orbit[42]. Likewise, Cosmos 2251, decommissioned in 1995, should have been deorbited by Russia. Due to a lack of legal mechanisms regarding the attribution of liability, and because mitigation guidelines are non-binding, neither Russia or the United States was ever considered as a wrongdoer. This can explain why none of them ever claimed for damage compensation, in addition to the fact that they both had no wish to generate a geopolitical conflict linked to their space assets. Besides, as explained in the description of insurers' mindset regarding deorbiting services, in the case of a collision between two insured satellites (which is not the case of Iridium 33 and Cosmos

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[41] Chatterjee, J. 2014. "Legal issues relating to unauthorized space debris remediation". 65th International Astronautical Congress. Canada.

[42] Kerrest, Armel. 2009. "Actualités du droit de l'espace : la responsabilité des États du fait de la destruction de satellites dans l'espace." In *Annuaire Français de droit international*, volume 55, 2009 pp 615-626.

2251, which were not insured), insurers would rather pay than investigate on the causes and liabilities of the collision.

For Armel Kerrest, this factor, added to "the fact that neither Russia nor the US was willing to launch a procedure", is "regrettable, for such an action could have helped establishing the legal precedents that are currently missing[43]". This is particularly blatant in LEO orbit. According to Christophe Bonnal, a CNES Senior Expert, in 2015, 68 % of the decommissioned satellites in LEO do not comply with international mitigation regulations and should have been already deorbited[44]. The absence of judicial precedent, along with the absence of legal specific definition of space debris, are both responsible for the inertia of the international community regarding space law as a key driver of space debris mitigation and deorbiting activities. This is clearly the line of Chatterjee: "If it is decided that space debris are not space objects, the protocol should determine under what conditions space debris may be removed or re-orbited in order to prevent collision or close encounters with valuable spacecrafts[45]". A possible solution that would necessarily require an international reflection about possible interceptions of third party's satellite with and without the prior consent of the launching State. Up to now, this question is far from being discussed (Chatterjee, 2014).

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[43] Sayings withdrawn from an interview led with Armel Kerrest, Space law expert, on March 13th, 2017.

[44] Bonnal, C. *Pollution spatiale, l'état d'urgence*. (Paris, Belin, 2016), 26-27.

[45] Chatterjee, J. 2014. "Legal issues relating to unauthorized space debris remediation". 65th International Astronautical Congress. Canada.

Appendix H: Approaching technologies

1. Passive Camera (monocular)

Flores-Abad et al reviewed the Passive camera technologies used in space missions and gave comments (Flores-Abad et al. 2014b). NASA took advantage of the fact that the HST is equipped with vision-based sensors to develop a method for estimating the angular rates of the HST (Thienel and Sanner 2007). The method was used in the estimation part of a tracking control scheme. Assuming that an object is not acted upon by any external force and moment, the motion of the target satellite was predicted. MIT, using 3Dvision sensors, proposed an architecture for estimation of dynamic state, geometric shape, and model parameters of an object in orbit, with potential application to satellite capturing (Lichter and Dubowsky 2004). A markerless visual 3D model-based servoing using a monocular camera mounted on the chaser. The system also included a robotic arm, and a chaser satellite mockup as shown in Figure 19.

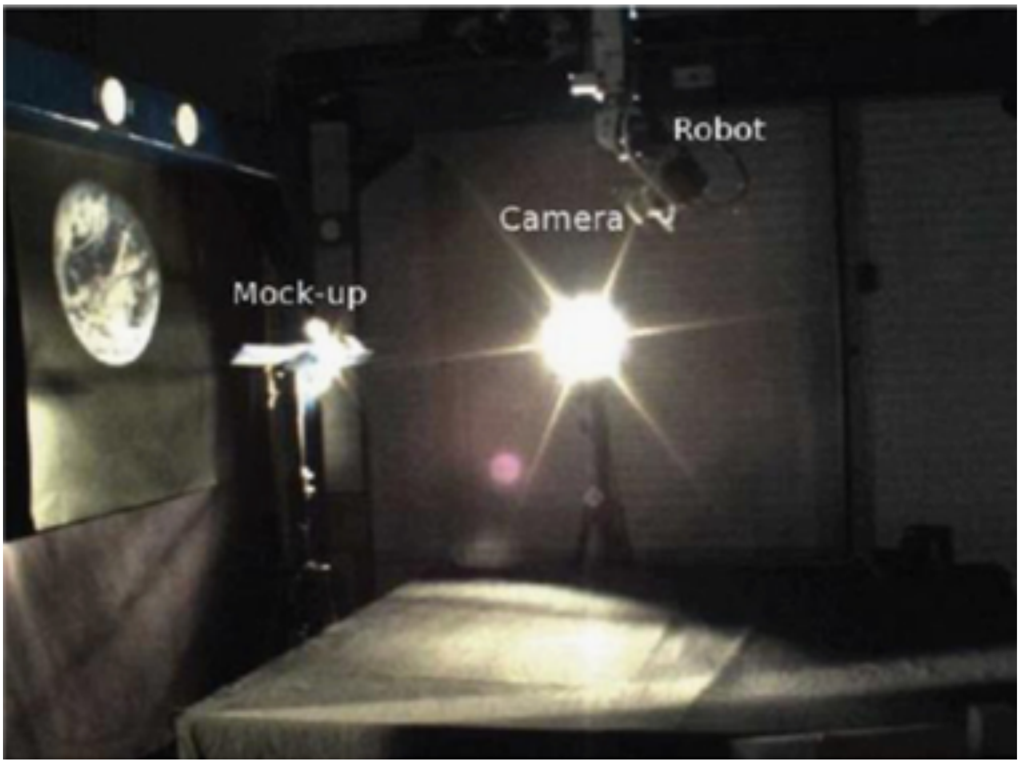

Figure 19 Experimental setup for pose estimation with a monocular camera

2. Stereo Camera

Based on stereo camera hardware, the Massachusetts Institute of Technology (MIT) Space Systems Laboratory is currently developing relative vision-based navigation and control techniques for autonomous inspection and 3D mapping of an unknown, uncooperative spacecraft that is spinning and tumbling at different rates. The vision-based system has been successfully demonstrated onboard the ISS and several tests have been conducted to analyze its performance. An image-based visual servoing considering the vibration induced by the manipulator's links motion was presented by (Sabatini et al. 2013). In order to increase the system robustness and to reduce the possibility of failure, an extended Kalman filter for the estimation of the feature motions was developed (Flores-Abad et al. 2014a).

3. Laser Range Finder

To allow a faster prediction, range data as measured by stereo vision or a laser range sensor was used to estimate the motion and the parameters of the target. (Inaba, Oda, and Hayashi 2003) introduced the design concept of a visual servoing system for a space robot and presented the experimental results using the Japanese ETS-VII test bed. They analysed the system requirements such as computing power, frequency and range of measurements as well as accuracy. Assistance from the ground was considered to choose a time line to maintain acceptable light conditions.

To perform the experiments, a Neptec's Laser Camera System was used for real time scanning of a satellite model attached to the manipulator arm, which was driven by a simulator according to orbital and attitude dynamics, as depicted in Figure 20 (Flores-Abad et al. 2014a).

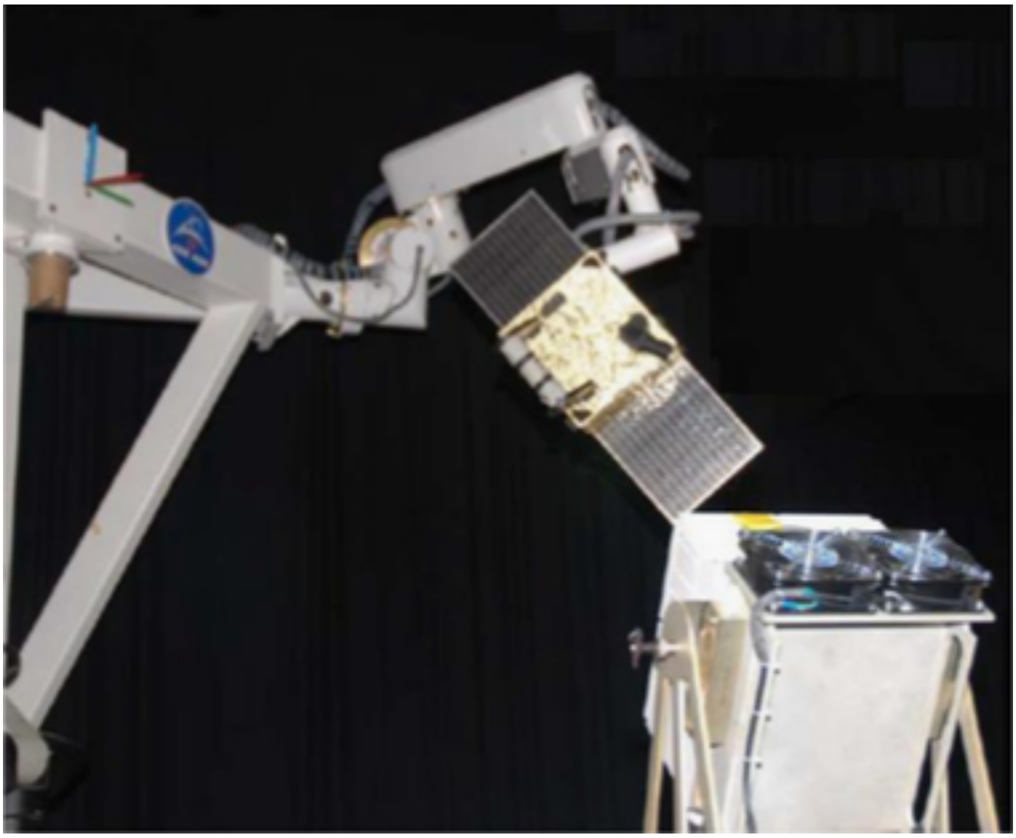

Figure 20 Experimental setup for satellite's position/attitude estimation using Neptec's laser range finder scanner

4. Scanning LIDAR

Scanning LIDARs use a narrow laser beam that is swept over the sensor Field of View (FOV) to obtain range measurements to objects within the scene as in Figure 21. The return from this laser typically illuminates a single detector as the laser direction is changed by a set of mirrors, lenses, and/or other devices. By combining knowledge of the laser direction and the measured range, a three-dimensional point cloud of the scene may be constructed.

Because they only use one detector (or a very small number of detectors), these sensors are relatively easy to calibrate. The user only needs to be concerned about the light sensitivity and timing for one detector. Additionally, because the LASER is typically directed by a system of lenses/mirrors, scanning LIDARs can point the narrow laser beam very precisely and create very high-resolution point clouds. Scanning LIDARs are also well suited for tracking a single object – once the laser "locks on" to the object (e.g. a reflector) it can track this object without worrying about the rest of the scene.

As their name implies, however, scanning LIDARs do contain moving parts that can wear out over time and potentially be a source of hardware failure. Further, if one desires a full 3D point cloud for an entire scene, it does take scanning LIDARs a finite amount of time to scan its entire field-of-view (FOV). The time required to compete this task varies widely amongst different systems. If the objects within the scene undergo substantial relative motion during the time required to scan the FOV there can be undesirable artifacts and/or motion blur in the resulting 3D point cloud (Christian and Cryan 2013).

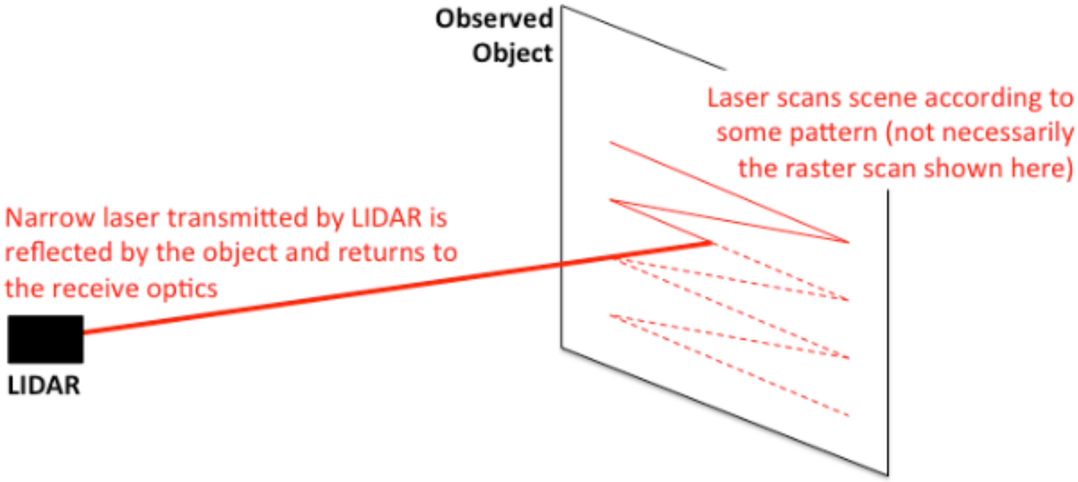

Figure 21 Notional depiction of a typical scanning LIDAR

5. Flash LIDAR

Flash LIDARs use Spatial Light Modulators (SLMs) to illuminate the scene and then use techniques from compressed sensing (CS) to reconstruct a 3D point cloud. This new class of LIDAR sensor, still under development at MIT, uses neither a scanning laser nor an array of detectors. Instead, Flash LIDAR is used to sequentially illuminate subsets of the scene with a sequence of known patterns. Then, the time history of the laser returns from the entire scene (for each of the illuminate patterns) is measured by a single detector. Now, by combining some assumptions on scene geometry (e.g. piecewise planar) with CS algorithms, the time history of the returns from a set of illumination patterns may be used to reconstruct an approximation of the 3Dscene.

While this type of LIDAR system has no moving parts and only a single detector, it must make approximations of the scene geometry in order to apply the CS algorithms. Further, this type of LIDAR system is still under development and is likely years away from practical application in the space environment (Christian and Cryan 2013).

Appendix I: Capturing technologies

1. Stiff connection capturing

Tentacles capturing

In ESAs e.Deorbit project, capturing using tentacles, can be performed either with or without a robotic arm. With a robotic arm used, tentacle capturing embraces the space debris with a clamping mechanism after holding a point on the target by the robotic arm. Finally, a velocity increment by the chaser will deorbit the combined object (Biesbroek 2012).

Aviospace is working on the project CADET which performs space debris capturing using tentacles. The tentacles are in a closed configuration made by belts to soften the contact between tentacles and target. The material of the belts can e.g., be Zylon + VITON or PES. Finite element models have been established to simulate the capturing process and assess the dynamic behavior during the chaser-target mating process. Several ground-based test concepts have been proposed, and the detailed design has been in progress since June 2014. (Chiesa et al. 2015)

Another type of tentacles is inspired by biology, i.e., linked to the morphology and function alike of the snake, elephant trunks or octopus arm. Two examples are provided in this paper. Yoshida and Nakanishi have proposed a concept of Target Collaborativize (TAKO) Flyer which contains a main service satellite and a TAKO Gripper. Since most of non-operational satellites are tumbling and failed to provide information to the chaser satellite, the TAKO Flyer is designed for collabrativizing the target by capturing the target and stabilizing its tumbling motion through several thrusters operation installed on the TAKO Gripper. (Yoshida and Nakanishi 2001)

McMahan has designed a continuum manipulator OctArm. OctArm version V contains three sections connected by the endplates. Each section is constructed with air muscle actuators, and it is capable of two axis bending and extension with nine degrees of freedom (McMahan et al. 2006)

Four types of tentacles capturing methods are displayed in Figure 22.

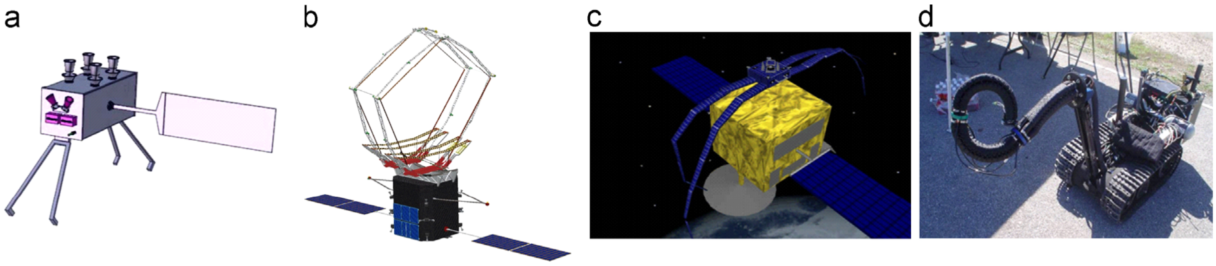

Figure 22 Tentacles capturing: (a) e.Deorbit . (b) CADET . (c) TAKO . (d) OctArm

Single arm capturing

Robotic arm technology has been applied in many on-orbit servicing missions, such as ETS-7 of JAXA , Canadarm2 , Orbital express of DARPA and many others . However, the targets in these missions are cooperative. For example, four markers are installed on the target satellite for rendezvous in ETS-7 mission. As what has been discussed above, space debris could be a non-operational satellite, an rocket upper stage or residuals from explosions. A space debris object will not provide any information to chaser satellite, and sometimes they are even tumbling. Therefore, it is more challenging to apply robotic arms in space debris removal missions as compared to on-orbit servicing missions.

DLR has been developing robotic technologies in a mission named Deutsche Orbital Servicing Mission (DEOS). The client satellite to be captured represents a non-cooperative and tumbling target which does not provide any information for rendezvous and capturing. The entire process from far range rendezvous to deorbiting is, however, to be performed in this mission (Reintsema et al. 2010).

A Chinese space program reported (Aolong-1) shows that there are some attempts to capture non-cooperative space objects by using single arm robot. Aolong-1, ‘The Roaming Dragon’, will complete a demonstration of space debris mitigation technology by using a small robotic arm to grab debris pieces and launch them toward the atmosphere.[46]

Figure 23 shows a single arm robot, DEOS.

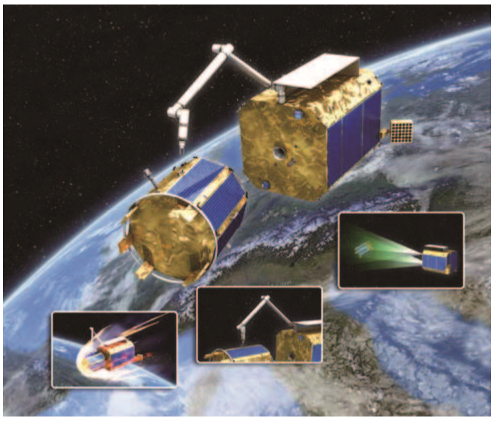

Figure 23 DEOS – A Satellite on-orbit servicing Technology Verification and Demonstration Mission

- **Multiple arms capturing**

Advanced Telerobotic Actuation System (ATLAS, Figure 24), a program from UK, consists of two robotic arms telerobotically controlled from ground (Ellery 1999). Multiple arms can be used in robotic assembling of a space structure, robotic refueling task and space debris removal.

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[46] http://spaceflight101.com/long-march-7-maiden-launch/aolong-1-asat-concerns/
http://spaceflight101.com/re-entry-aolong-1-space-debris-removal-demonstrator/

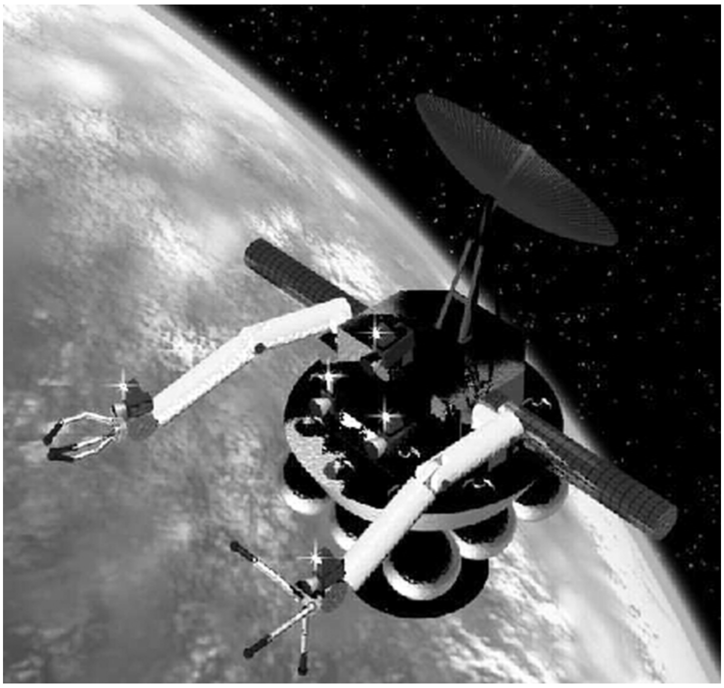


Figure 24 ATLAS in-orbit servicing robotic freeflyer

Mechanical effector

A mechanical effector is one of the most important parts in a robotic arm. It is directly involved in the capturing motion and contacts with the target. The success of the space debris removal mission depends highly on the reliability and stability of a mechanical effector. Therefore, mechanical effector plays an crucial role in either single or multiple robotic arms capturing. There are several concepts of mechanical effector for capturing a space debris object, such as a probe for the nozzle cone of an apogee kick motor, payload attach fitting (PAF) device, articulated hand, two fingers mechanism and universal gripper. However, this gripper is not adaptive to capture a free-flying object since a force closure needs to be formed during capturing. Five mechanical effectors are shown in Figure 25.

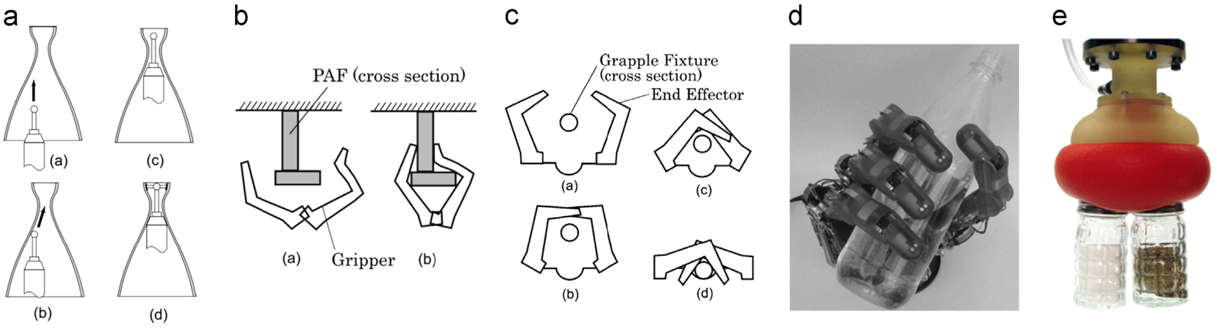


Figure 25 Mechanical effectors

2. Flexible connection capturing

For tentacles capturing and robotic arm capturing, the connection between chaser satellite and target is stiff. This makes the composite controllable and stable. However, the mass and cost are dramatically increased. To overcome this drawback, flexible connection capturing methods in which the end effector and chaser satellite are connected by a tether, are proposed.

- **Net capturing**

Net capturing is regarded as one of the most promising capturing methods due to its multiple advantages e.g., it allows a large distance between chaser satellite and target, so that close rendezvous and docking are not mandatory; it is flexible, light weighted and cost efficient. However, several research areas related to net capturing such as modeling of a net, contact influence, deploying process investigation and tumbling compatibility still need to be developed.

ESA has sponsored the Robotic Geostationary Orbit Restorer (ROGER) whose objective is to transport a target into a graveyard orbit. The end- effector in this project can either be a net or a gripper mechanism (Bischof 2003).

Net capturing method is one of several concepts for ADR proposed in e. Deorbit project (Billot et al. 2014).

At Politecnico di Milano Dipartimento di Ingegneria Aerospaziale (PoliMi-DIA), a project named Debris Collecting Net (D-CoNe) has been developed (Lavagna et al. 2012).

University of Colorado at Boulder has proposed a net concept called REsearch and Development for the Capture and Removal of Orbital Clutter (REDCROC) as well (Zinner et al. 2011).

Four different concepts are provided in Figure 26.

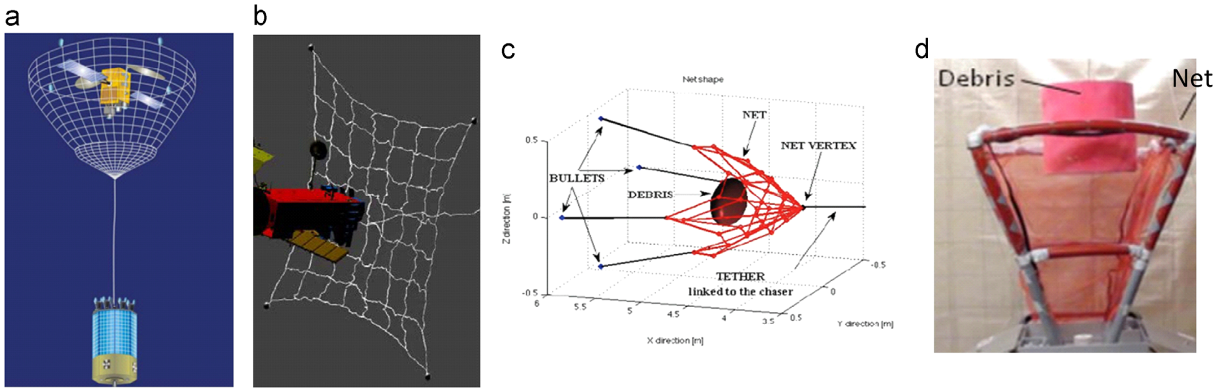


Figure 26 Net capturing: (a) ROGER . (b) e.Deorbit . (c) D-CoNe . (d) REDCROC .

Surry Space Center, together with other eight partners, is going to launch a mission called RemoveDEBRIS, which is a contract of €12 million funded by European Commission (Pisseloup et al. 2016). The mission will consist of a microsatellite platform (chaser) that ejects 2 CubeSats (targets). These targets will assist with a range of strategically important ADR technology demonstrations including net capture, harpoon capture and vision-based navigation using a standard camera and LiDAR (Figure 27). The chaser will also host a drag sail for orbital lifetime reduction. The mission baseline has been revised to take into account feedback from international and national space policy providers in terms of risk and compliance and a suitable launch option is selected. A launch in 2017 is targeted (Forshaw et al. 2016).

Figure 27 RemoveDEBRIS

- **Tether–gripper mechanism**

Tether-gripper mechanism is generally a gripper at the end of a tether. Tether–gripper mechanism is more stringent and more complicated than net capturing in operation. The tether–gripper is the other mechanism introduced in ROGER besides net. The principle of the tether–gripper mechanism is similar to the net capturing mechanism. The end-effector in the tether–gripper mechanism is shot as a 3-finger gripper to capture a target (Bischof 2003).

Chinese researcher Huang proposed a tethered system called Tethered Space Robot (TSR) with similar concept. Figure 28 shows two different concepts of tether-gripper.

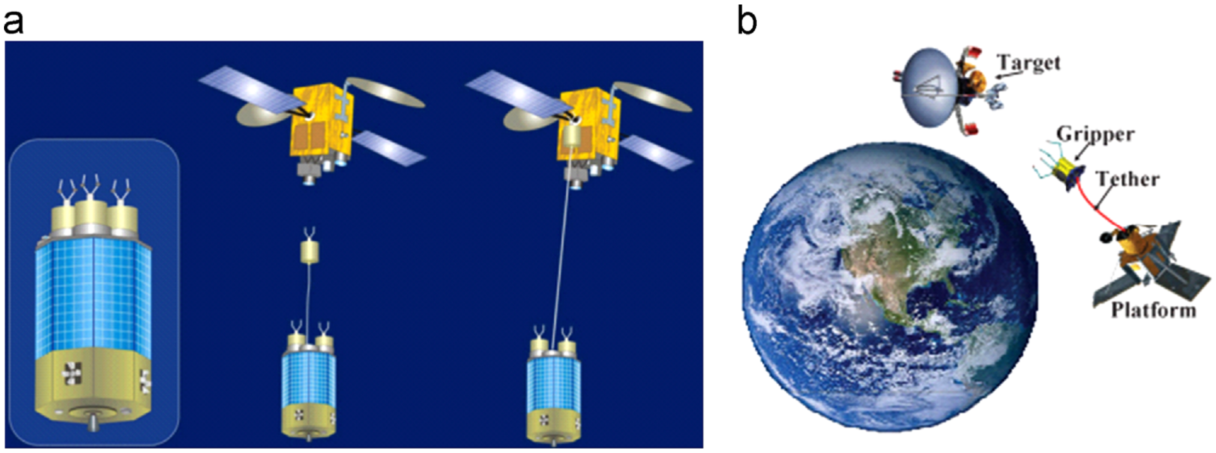


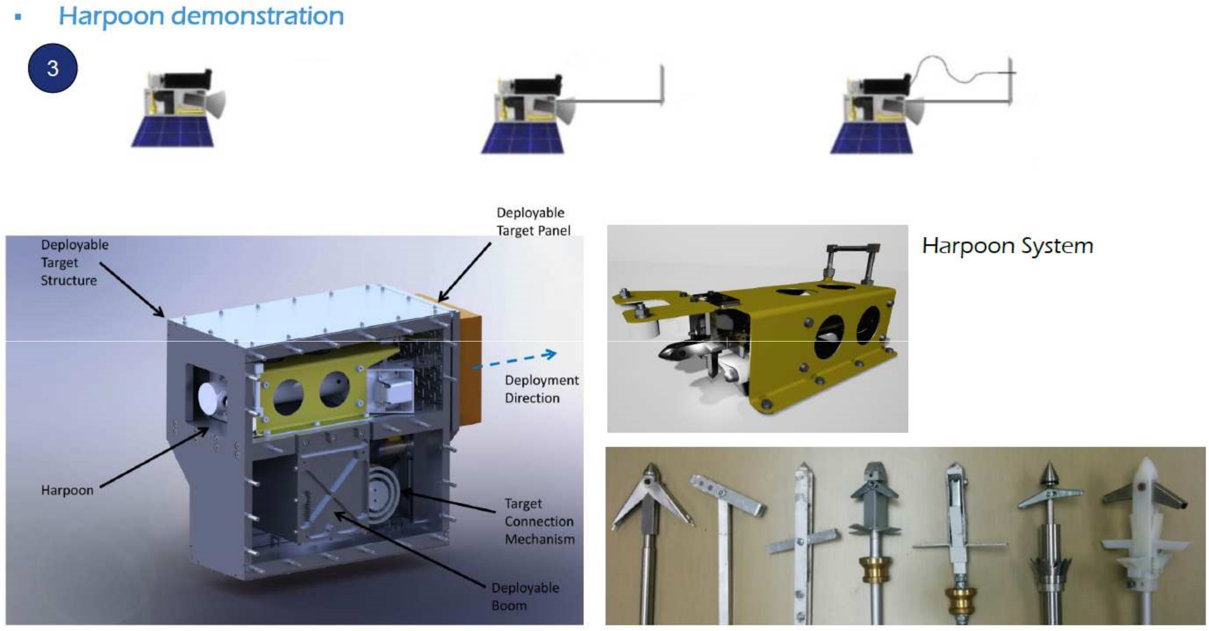
Figure 28 tether-gripper: (a) ROGER . (b) TSR

- **Harpoon mechanism**

A harpoon mechanism with barbs on its tip can be shot from chaser satellite and penetrate itself into a large space debris object. Chaser satellite will pull the debris re-enter or to a graveyard orbit afterwards. It is considered as an attractive capturing method because of its compatibility with different shaped targets, stand- off distance allowed and no grappling point needed. Since penetrating happens in this case, the risk of generating new space debris is relatively high. Moreover, it is not capable to treat a target with high tumbling rate.

Harpoon capturing method is also one of the concepts from e.Deorbit. Based on the trade off results with net method by ESA, harpoon mechanism earned a higher score since cost efficiency and higher Technology Readiness Level (TRL) can be obtained (Billot et al. 2014). As mentioned, RemoveDEBRIS will test the harpoon method in 2017 (Forshaw et al. 2016). Figure

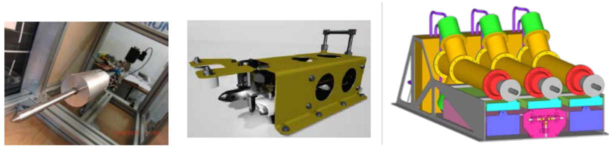
29 shows the harpoons introduced in RemoveDEBRIS (Pisseloup et al. 2016). Figure 30 shows the harpoons developed by Airbus Defence and Space for different projects (Wayman, n.d.).



Harpoon Target Assembly Payload

Projectile Prototypes and Evolution

Figure 29 Harpoons in RemoveDEBRIS



R&D Harpoon

RemoveDebris Harpoon

Clean Space Harpoon

Figure 30 harpoons developed by Airbus

- **Adhesive method**

Some institutes (JPL, Technische Universit¨at Braunschweig, etc.) have been developing a gecko adhesive grappling tool that uses microscope angled hairs to stick to the surface of a target. The adhesion is based on van der Waals' force and can be turned ON and OFF by controlling the loading direction. Figure 31 shows the gecko material produced by the Leibniz In-stitute of New Materials.

Figure 31 Gecko materials produced by the Leibniz In-stitute of New Materials

Appendix J: Removing technologies

1. Propulsion removing

Chemical propulsion (CP) are the most mature system in space industry in terms of change the velocity of a spacecraft. From the very beginning of space history, the CP systems plays a leading role in propelling the satellites. But, the specific impulse of CP systems is somehow low. Deorbiting satellites by using CP systems requires a significant amount of propellant, which means the cost of the systems is very high.

Electrical propulsion (EP) systems are indeed characterized by low propellant mass requirements. In the past years, a series of missions using EP as primary propulsion (e.g. GOCE, SMART-1, Artemis, Deep Spcae1, Hayabusa) succeeded. Boeing's ABS-3A, the world's first all-electric propulsion satellite has commenced its duty in 2015. The EP systems are mature enough to be a suitable candidate for providing propulsion for an active debris removal system.

(Covello 2012) investigated the feasibility of using Electrical propulsion (EP) systems to deorbit a space debris. The results of a similar analysis performed for a classical CP system are then presented and the two options are compared in terms of total cost of the mission. The study shows that the EP concept have a slight advantage. With the progress of EP system, the cost of the mission will be lowered in the future.

2. Drag augmentation system

Increasing the area-to-mass ratio of a space debris object is a way of increasing the atmosphere drag influence. Drag augmentation method allows a large distance between chaser satellite and target. Therefore, no close range rendezvous or docking is required in this method. It reduces the requirements for chaser satellite since the reentry process is performed by the atmosphere drag influence instead of chaser satellite. In addition, it is compatible with different sizes of space debris. Due to the atmosphere distribution in space, the targets removed using this method should be orbiting in LEO. Three methods to remove space debris based on this concept are presented in Figure 32.

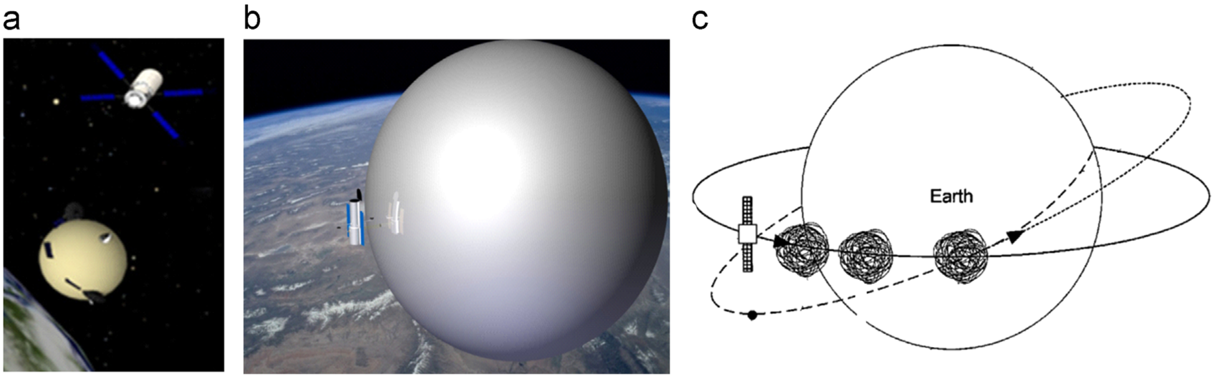


Figure 32 Drag augmentation methods: (a) foam method. (b) Inflated method. (c) Fiber-based method.

3. Electro-dynamic tether

Electro-dynamic tether removal method is originally used in orbit transfer and orbit manoeuvring. It is a method taking advantage of the geomagnetic field to re-enter. In this aspect, propulsion system is not mandatory during re-entry. (Nishida et al. 2009) uses a small satellite to deploy tether technology and to deorbit a space debris (Figure 33).

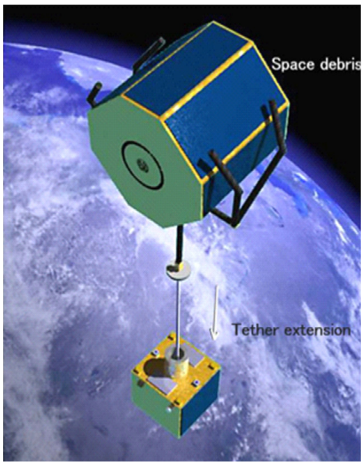


Figure 33 EDT from JAXA

4. Solar radiation force

Using solar radiation force to remove space debris is a method for the non-operational satellites whose propulsion system fails or the propellant is not enough to reenter, but whose control system for solar sails is still working. Solar sail propulsion method was first validated by JAXA in 2010 (Tsuda et al. 2011). Figure 34 shows the fully extended mode (upper) and final assembly mode (lower).

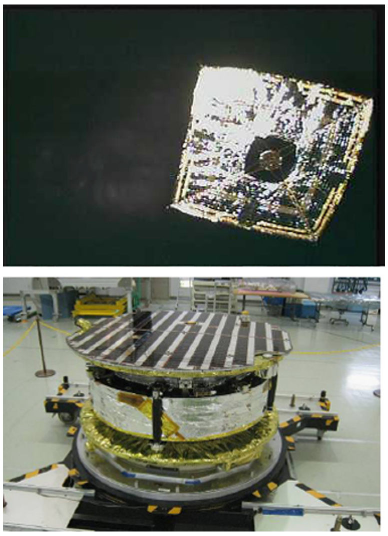


Figure 34 JAXA's solar sail project, IKAROS

5. Contactless removal methods

Contact between chaser satellite and target during capturing and removal will influence the stability of the entire system. Contactless method, which means no direct contact happens during the entire removal process, can overcome these defects.

- **Artificial atmosphere influence**

The principle of artificial atmosphere influence is to propel atmospheric particles in the path of a debris object. As a result, the velocity of the debris is decelerated and its altitude is lowered. Figure 35 (a) shows the concept of Artificial atmosphere influence.

- **Laser system**

Pulsed laser beam shoots onto a space debris to decrease its velocity and lower its altitude. However, the risk of new debris generation is significantly high using laser system. This laser system can be located at ground-based equator, ground-based polar region or on board. Figure 35 (b) shows a ground-based Laser Orbital Debris Removal (LODR) system.

- **Ion Beam Shepherd**

Ion Beam Shepherd (IBS) is a concept of ejecting highly collimated neutralized plasma beam onto a debris object thus lowering its altitude. Figure 35 (c) shows a concept of IBS.

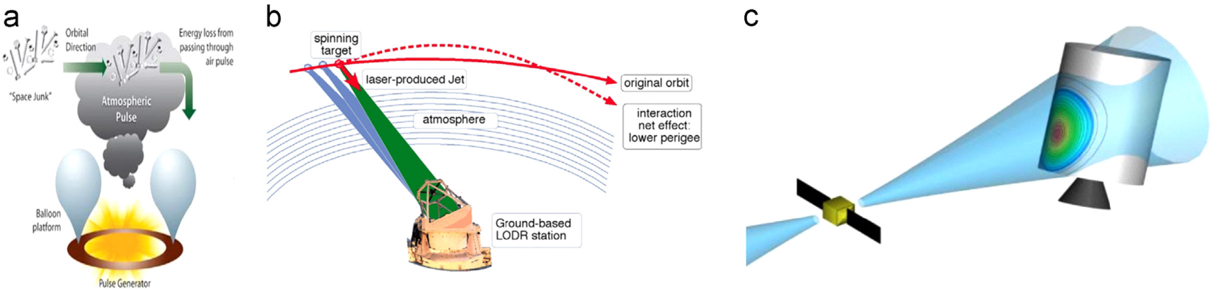


Figure 35 Contactless removal methods: (a) Artificial atmosphere. (b) Laser system. (c) IBS.

6. Contact removal methods

Contact removal method is a concept that takes advantage of a direct interaction between chaser satellite and target during the removal process.

- **Slingshot method**

Texas university has developed a satellite called Sling-Sat Space Sweeper (4S), which is designed for saving energy for ADR since it removes multiple targets in one launch. The satellite can capture a space debris and eject it towards the earth then slide to another space debris object applying the momentum generated from the ejection. Figure 36 shows a concept designed by Texas A&M University (Missel and Mortari 2011).

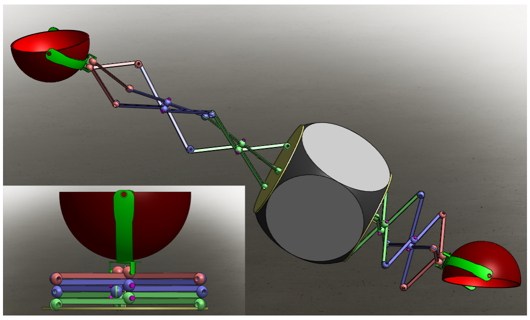


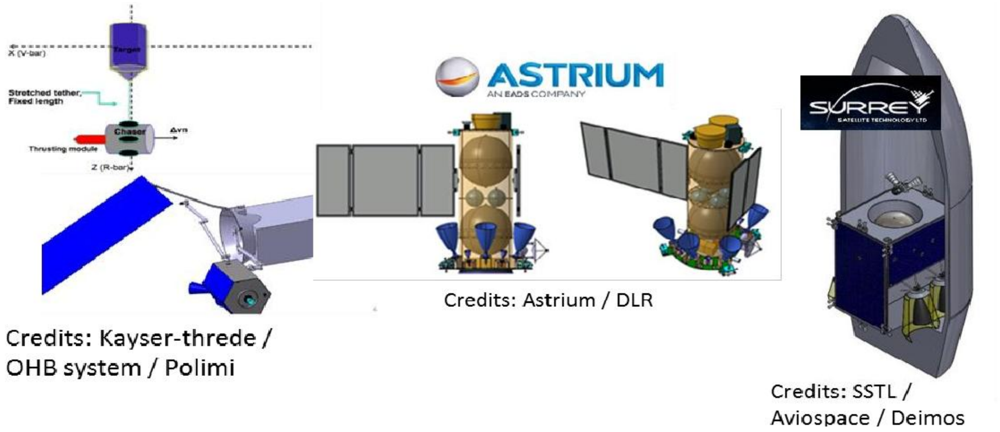
Figure 36 Concept of Slingshot satellite

Appendix K: Projects lead by ESA

1. Clean Space

ESA is pursuing technological systems, under its Clean Space initiative for their first Active Debris Removal (ADR) mission, targeted at the removal of Envisat. To identify the feasibility of setting up this mission, three contracts were awarded:

- SSTL, Aviospace and Deimos
- Kayser-Threde, OHB System, Polimi
- Airbus Defence and Space



Credits: Kayser-threde / OHB system / Polimi

Credits: Astrium / DLR

Credits: SSTL / Aviospace / Deimos

Figure 37 Companies awarded contracts

These three companies were awarded these contracts, with the aim of analysing the readiness level of the market (industry) and if such mission, which technically would be a service could be successful and if they could get paid for it. Secondly, if the market was ready for debris removal.

Nowadays, innovation in space and on the ground is the pursuit of eco-friendly technologies and design. This is a path that ESA has decided to follow suit on and an opportunity for the European Space market. The need to diminish current debris, to preserve the orbital environment requires new technological approaches to remove debris.

Part of the Clean Space initiative is the eDeorbit, which aims to remove a large piece of debris from LEO.

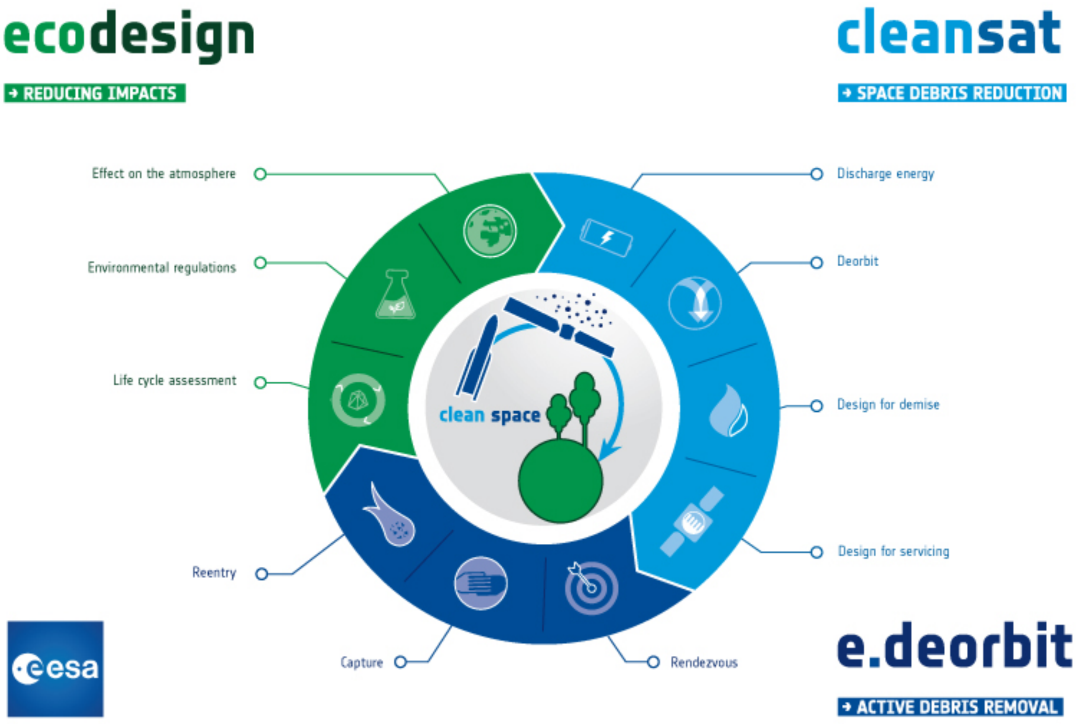


Figure 38 Clean Sat Information Diagram

2. E.Deorbit

The ESA is evaluating the possibility of an ‘active debris mission’, e.Deorbit. According to the ESA website, the mission would target an ESA owned uncooperative satellite in low earth orbit, capture it, then have it burned up safely in atmospheric re-entry. The agency is reviewing the possibility of using two ways of approaching and capturing targeted debris: a robotic arm or with the use of a net.

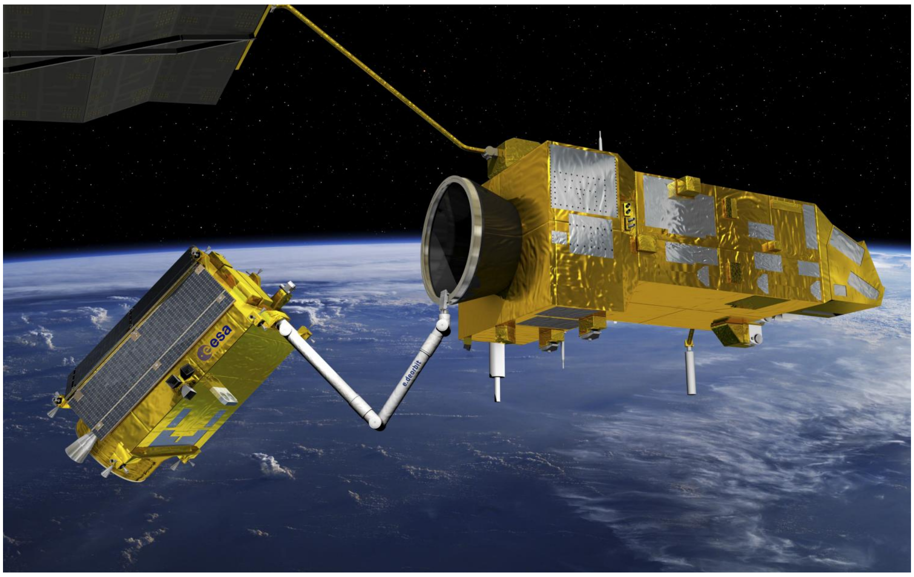


Figure 39 e.Deorbit Robotic Arm

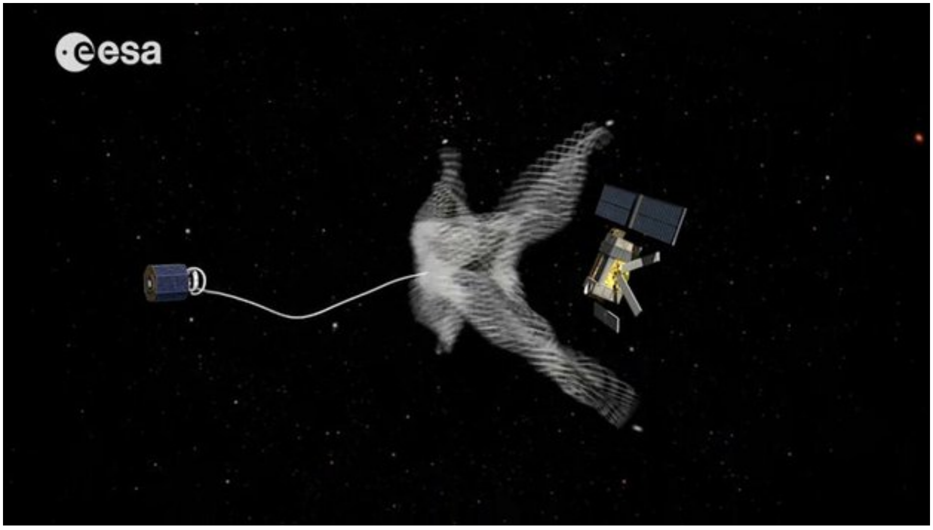


Figure 40 e.Deorbit Net

Envisat will continue to orbit for 150 years if nothing is done. According to MDA, the robotic arm scenario to grab the launch adapter ring of the satellite, is a better option because the satellite is spinning. The company suggests capturing Envisat and then putting it in on a trajectory where it would be able to deorbit.

The e.Deorbit mission, which will consist of a 1,300kg net-carrying satellite on top of a Vega launcher. Once launched in space it will enter the same polar orbit as Envisat. After intercepting Envisat, the satellite carrying the net will synch orbits with its target and fire the net at Envisat. Once captured, the e. Deorbit satellite will become a tug and engage its engines, hopefully pulling Envisat to a controlled but fiery demise, high in the atmosphere.

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