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"ORBITAL DEBRIS: A GREAT BUSINESS OPPORTUNITY"

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Abstract

Since the beginning of the space age more than seventy years ago, humanity has launched many thousands of satellites into orbit. Most of these satellites and their upper-stage rockets are now defunct and uncontrollable debris objects, posing an increasing risk of collision with other spacecraft and their operations. When debris objects collide with defunct or functioning spacecraft smaller objects are spewed, which greatly increases risk. A small fragment, traveling at orbital velocities, can perforate the hull of crewed spacecraft, causing quick depressurization and fatalities. We hear many concerns about orbital debris, often associated with recommendations to clean debris from Earth's orbits. There are similar concerns about pollution on Earth's surface, seas, and air. However, we have witnessed significant improvements on Earth only when terrestrial wastes are processed and transformed in useful assets, such as fertilizers, building materials, or energy. The solution in orbit is not different. If we see orbital debris remediation only as an expense, it is unlikely that real clean-up will begin. The good news is that orbital debris – like terrestrial waste – has value too. If collected, reprocessed, and reused, instead of simply deorbited, orbital debris clean-up can mark the starting point of cis-lunar industrial development. It is therefore urgent to begin dealing with orbital debris clean-up in terms of feasibility, cost estimation, and investment return, in other words, as a business proposition. There are a variety of technologies being developed for dealing constructively with orbital debris or with spacecraft nearing End-of-Mission. Polar orbits between 600 and 1000 km altitudes are particularly crowded and at risk. For large and medium-sized masses (bus-sized, multi-ton masses down to 10 cm diameter bodies) propellant-less and touchless technology vehicles look potentially useful. For over a million debris objects smaller than 10 cm across down to the size of a pea, Whipple shielding on spacecraft is insufficient. Net and catcher technologies for them are slowly being developed, but far too slowly. The scope of this paper is not to give a complete survey of the many ongoing research efforts on the orbital debris theme, but to give sound and proper political and financial arguments to encourage quickly moving to a business approach, very much more effective, vs. a mere problem-solving one.

A SUMMARY HISTORY OF ORBITAL DEBRIS

Within ten years after the launch of Sputnik in 1957, the Soviet Union and the United States had launched 83 spacecraft. Because no nation-state objected to leaving upper rocket stages and other waste in orbit during this span, the practice became firmly established and was not addressed in the 1967 Outer Space Treaty[1]. In general, spacefaring nations and private individuals believed in the "Big Sky" theory, i.e., that orbital space around the Earth is so large that orbital debris would never become a problem. The 2007 words of an Iridium Vice President are emblematic of this attitude. When asked about the chance that an orbital debris object could hit an Iridium satellite, his reply was that the risk was one in 50 million[2]. Eighteen months later, a defunct Russian satellite struck a working Iridium 33 satellite, destroying both and creating over 2500 trackable debris objects and many more untrackable pieces of shrapnel[3]. Collisions and explosions among working and defunct spacecraft eventually created over a million objects that can destroy spacecraft and risk lives. Moreover, with the advent of satellite constellations that have doubled the number of functioning spacecraft, the additional orbital crowding has commensurately increased the risk of collisions. Illustrative of this increased risk is the recent report by SpaceX that their Starlink satellites have had to make over 25,000 collision-avoidance maneuvers over the last six months.[4]

ORBITAL DEBRIS, A THREAT TO SPACE NAVIGATION

Space debris encompasses both natural meteoroids and artificial (human-made) debris in orbit, the latter including defunct upper rocket stages and satellites, loose fragments from rocket explosions and collisions, and even paint flakes.[5] Between 1968 and 1985, tens of anti-satellite tests by the Soviet Union and the United States added orbital debris. More recent anti-satellite testing has contributed to the problem. Finally realizing that the anti-satellite tests were creating a

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major hazard to future space activities, seven spacefaring nations signed an anti-satellite test ban agreement in 2022.[6] However, the number of orbital debris objects has continued to grow with the birth of the new space age, which we may symbolically identify in 2004 when ScaledComposites won the X-Prize with its SpaceShipOne fly at suborbital altitude. This suborbital event by a private company was soon followed in 2008 by the first successful orbital flight of the privately funded SpaceX Falcon I rocket, then the 2015 first successful landing of a Falcon 9 *reusable* booster by the same company. Along with strides in miniaturization and off-the-shelf equipment, these two threshold events by SpaceX led to plunging costs in rocket production and launch, which has in turn led to an exponential jump in the number of launches of spacecraft to orbit, as well as emerging rocket companies.

Figure 1 represents the numerical evolution of orbital debris, according to ESA, by object class: PL Payload PF Payload Fragmentation Debris, PD Payload Debris, PM Payload Mission Related Object, RB Rocket Body, RF Rocket Fragmentation Debris, RD Rocket Debris, RM Rocket Mission Related Object, UI Unidentified. Nowadays more than 30.000 objects are estimated flying from LEO to GEO, with the highest concentration in LEO (see Figure 2).

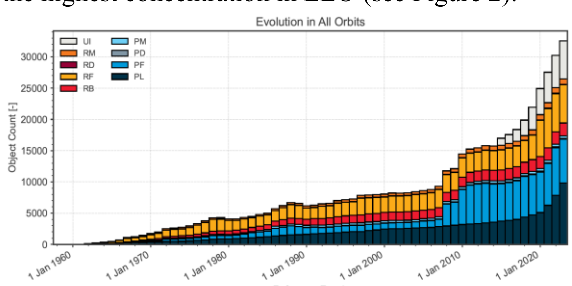

Figure 1 Evolution of number of objects in geocentric orbit by object class[7]

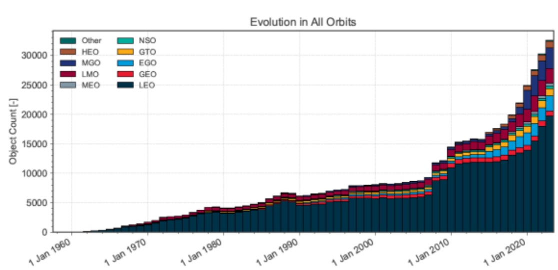

Figure 2. Evolution of the number of objects by orbit

Based on statistical models produced by ESA's Space Debris Office, it is estimated that there are 36,500 objects larger than 10cm, 1 million objects between 1-10cm, and an extraordinary 130 million objects between 1mm to 1cm[8].

Most of the orbiting satellites are now inactive, dangerous wreckages, which pose an increasing risk of collision with other satellites and the operations of manned spacecraft.

When wreckages eventually collide, an unpredictable mass of smaller debris is produced, which greatly increases the general risk: any small fragment, traveling at orbital speed, can open holes in the hull of manned spacecraft, causing quick depressurization. The above situation is now well known, and we hear many concerns about that, often associated with recommendations to start recovering, cleaning, and claiming Earth orbit.

Risk of space debris and Kessler effect

The Kessler Syndrome is a theory proposed by NASA astrophysicist Donald J. Kessler in 1978. Kessler published a paper called "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt"[9], which predicted that, by 2000, the density of space debris in Earth's orbit would be so great that random collisions would be inevitable, and that outcome of these random collisions would be more debris, and subsequently more collisions.

Several authorities, not just related to space, expressed their concerns about the continuous growth of orbital debris, reporting the risk of the Kessler effect. The Organization for Economic Cooperation and Development (OECD) published a book[10], in which the risk of a Kessler syndrome is clearly addressed: *"Orbital debris has increased remarkably in the last 15 years and the socio-economic impacts of a major space debris accident could be dramatic due to cascading effects. The overwhelming concern is that orbital debris density reaches such levels that it triggers the so-called Kessler Syndrome – a catastrophic and irreversible chain reaction of on-orbit collisions between debris and operational satellites. Certain high-value orbits may become unusable, while debris concentrations could even block access to higher orbits."* OECD highlights the highly detrimental social impact of such a threat on the global economy and daily life of planet Earth's citizens and suggests urgent measures to be undertaken, first estimating the loss associated with excessive debris in Earth's orbit in monetary terms: *"An experimental model has been developed to assess the economic effects of a collision event through global value chains. It estimates worldwide monetary losses in the case of Kessler Syndrome to USD 191.3 billion."*

Orbital man-made debris adds to natural micrometeorites

Not only man-made debris threats space navigation. Natural micrometeorites, similar sized, are crossing Earth's orbit as well, in an unpredictable way, especially the smallest ones. Natural micrometeorites constitute a risk for space navigation as well and may contribute, though in minor part, to a possible Kessler effect. Micrometeorites are, of course, a totally different matter, from the mitigation and remediation point of view, since such objects come from outside Earth's orbit, and cannot be caught nor collected. Yet, the collision of a spacecraft with such kinds of objects can maybe be avoided, by means of some proper techniques, such as laser destruction. A robust enough external outer hull could resist to any high-speed "bullets". It is not reasonable to imagine each medium and small satellite equipped with laser defense systems or a thick outer shell.

However, at least as far as big spacecraft are concerned, the research for laser destruction and robust outer hull might be a common theme between mand-made debris and natural micrometeorite risk mitigation.

THE REMEDIATION STRATEGIES ADVANCED BY THE MAIN SPACE AGENCIES

NASA's ultimate refocusing

While previous considerations of orbital debris remediation have focused on removing large debris to minimize the amount of debris in space over long timescales, the new NASA OTPS report[11] takes a more holistic approach to remediation, by including non-removal approaches for large debris and removal approaches for small debris. Based on current information, the report found that the most effective remediation methods for reducing risk could involve nudging large debris away from collisions, rather than completely removing them from orbit, and removing small debris in the 1-10 cm range with laser systems. Ultimately, the report called for a more rigorous and wide-reaching analysis of the potential costs of orbital debris for satellite and spacecraft operators and to get better cost estimates for performing novel types of debris remediation. The first step, it says, would be to gather feedback from the space community, and then use that feedback to prioritize follow-on work to build on current findings.

ESA requirements on space debris mitigation

The Requirements on Space Debris Mitigation for ESA Projects[12] is targeted to limit the production of new orbital debris, in particular in the LEO and GEO protected areas, and on risk reduction measures in the case of re-entries of space systems or their components into the Earth's atmosphere. During the last quarter of 2022, after having developed a deep study and refocusing of the debris matter, ESA conceived The Zero Debris strategy, showing the Agency's ambition to clean the space environment [13]. Based on the catastrophic forecast of nearly 400,000 objects larger than 10 cm. in 2025 (see Figure 3), the ESA document issues several recommendations and a first roadmap of what is to be done. The main recommendations include mandatory active debris removal services for all missions; clearance of the valuable orbital regions after 'end of mission'; increasing resilience of onboard systems; enhancing accuracy and efficiency of collision avoidance and mitigating risk for active missions; the clear decision-making process; Global Navigation Satellite System (GNSS) orbital regions to be recognized as valuable orbital regions.

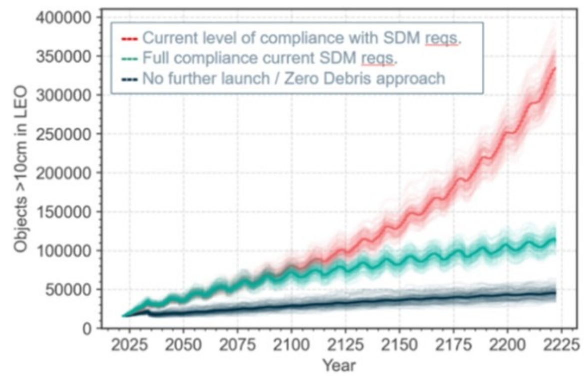

Figure 3. Evolution of the number of objects in Low Earth Orbit over 200 years for different scenarios

The technical recommendations summary provided by ESA provides excellent measures, for the mitigation, prevention, and avoidance of orbital debris and for the reduction of related risks. Yet, the only (implicit) considered return of investment is based on the reduction of damages due to potential collisions and consequent conservation of a navigable space environment. No doubt that the above would be a remarkable return if calculated. No consideration is provided, about a possible business approach, to be profitably added (not substituted to) the mere mitigation/remediation strategy.

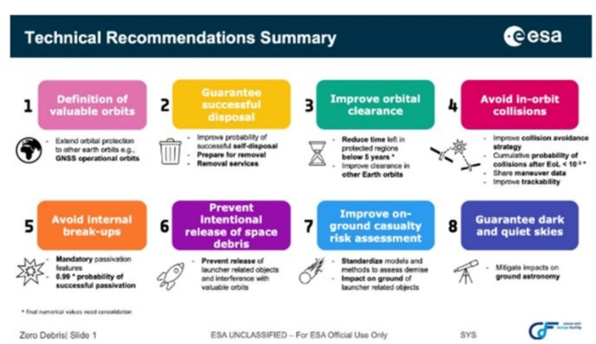

Figure 4. Overview of the technical recommendations proposed by the ESA CDF team

ELEMENTS FOR AN ORBITAL DEBRIS BUSINESS PLAN

A meaningful precedent: Wastes Management on Earth

However, we know that there is a similar general concern about pollution on Earth's surface, sea, and air. We have witnessed significant progress only when terrestrial wastes commenced to be processed and transformed into useful assets, such as fertilizers, building materials, and energy.

Global Return on investment in waste industrial management shows a constantly increased value, from 2010 to 2023[14]. In many regions, however, other strategies – mainly based on public expense, rather than on a business approach – keep on resulting in catastrophic outcomes, including cities periodically suffocated by wastes in the streets and smelly/polluting landfills. On the contrary, the reuse of waste brings energy production to feed whole urban districts, and several by-products for building, agriculture, and other industrial uses, with consequent profit and jobs.

Why a similar strategy is not yet advanced for orbital debris? Is such tardiness due to the historically high cost of orbital operations? Or to ideological/political bias? The first cause, at least, is changing because of recent progress in rocket reusability. For the second case, we shouldn't just wait for the incoming financial convenience to overcome the differently motivated resistances: everywhere potentially feasible proposals should be advanced and discussed.

Orbital Debris: how and when the threat will be met

The problem in orbit is not different from the waste management on Earth's surface: until we will see orbital debris only as an expense of public money, it is quite unlikely that a real cleaning action will take off. The good news is that orbital debris – just like terrestrial wastes – is valuable too. If collected, reprocessed, and reused, space debris can mark the starting point of orbital industrial development. It is therefore very urgent to begin working on this issue in terms of feasibility, cost estimation, and return of investment, i.e. business plan.

Waste asbestos reutilization: similarities and differences

A similarity could be seen between orbital debris and asbestos mining and use since both are time-limited businesses. Why? Because in both cases the main source materials will come to an end, at a certain point in history. Such a consideration seriously prevented, so far, any investment in the expensive industrial equipment needed for inerting asbestos. Just to mention a first similarity, on the topic of elimination of the high risk for health represented using such minerals for building and thermal insulation, several recommendations exist, by EU, to avoid any disposal of materials containing asbestos in landfills or similar waste disposal facilities. In a 2015 resolution[15], the European Economic and Social Committee strongly prescribed inertization[16]: "The EESC calls on the Commission to promote research and innovation to find sustainable technologies for the treatment and inertization of waste containing asbestos with a view to their safe recycling, re-utilization, and the reduction of their delivery to landfills." Several tens of patents were deposited in Europe, concerning technologies and industrial plants – e.g. sintering, vitrification, and other kinds of inerting procedures – that would cancel any harmful effect of asbestos, providing, concurrently, useful building materials. Let's note that, in this case, the EU committee was brave enough, to suggest re-utilization (not the same courage was shown on space waste, so far…). However, little luck has been had so far with both patents and recommendations for asbestos waste re-utilization. The main reason? In a few years, products using asbestos will no longer be produced – and so will the market for its reuse in secondary products will eventually vanish.

However, that will not be the case for Orbital Debris, for several reasons.

First, the number of spacecraft launched into orbit is growing exponentially, in a directly proportional way to the plunging launch cost. The number of new debris objects in orbit should decrease with the application of due policies and the development of recovering and reusing industrial activities. Also, full rocket reusability will progressively limit the number of upper stages remaining in orbit, though small rocket upper stages will likely remain in use for many years to come. Finally, the number of existing debris objects is so high (in the order of millions) that it is hard to predict when they will be fully eliminated.

Second, let's think about the industrial activities related to debris recovery and reuse, just to make a few examples: production of new "raw materials" (e.g. powders or 3D printing) from reprocessing the recovered objects; production of new components for satellites and spacecraft in orbit assembling and refurbishing; fuel production from reprocessed materials; satellites and spacecraft maintenance and relocation; large objects parked temporarily in salvage orbits for later utilization. And, of course, future use of orbital waste in orbiting workshops and industrial production plants. Cislunar activities will be strongly supported and initially facilitated by the waste management industry, as well as future human settlements. Last, but not least, there will be other kinds of waste produced in space by industrial activities and humans living and working in orbiting habitats. Those newer kinds of waste will need to be

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managed, reprocessed, and reused, in a general Circular Space Economy (CSE).

Orbital Debris Removal, Salvage for Reuse, and Spacecraft Mission Extension: a quickly growing market

The Global Active Space Debris Removal market is anticipated to rise at a considerable rate between 2022 and 2030. The market is growing steadily, and with the rising adoption of strategies by key players, the market is expected to rise over the projected horizon[17].

Many new space and traditional aerospace dealers are active in the market of Orbital Debris Removal, Orbital Services and Logistics, including Aerospace Corporation, Agile Space Industries, Airbus, Allocation.Space, Altius Space, Any SignalInc, Argo Space Corp, Ariane Group, Arkisys, Aryabhata Research Institute of Observational Sciences, Astroscale, Atomos, AXAXL, Blue Origin, Cislunar Industries, Cateni Inc, Clear Space Today, Com Spoc, Dawn Aerospace, DLA Piper, D-Orbit SpA, Electro-Optic Systems Ltd, Exo Analytic Solutions, Exodus Space Solutions, Exo Launch, Exo Trail, Gitai Inc, HEO Robotics, iBoss, IHI Aerospace Co Ltd, Impulse Space, Infinite Orbits, Innovative Solutions in Space B.V., ISRO, Kall Morris Inc, Kinetik Space, Kurs Orbital, L3HarrisTechnologies, Leaf Space SpA, Lockheed Martin Corporation, Maxar, Momentus Inc, Moog Inc, Motiv Space Systems Inc, Neumann Space, Northrop Grumman Corporation, Oceaneering Space Systems, OHB System AG, OrbitFab, Piap Space, Protean Industries LLC, Quantum Space, RedWire Space, Scout, Secure World Foundation, Sierra Space, SKY Perfect JSAT Corporation., SkyCorp, Space Dynamics Laboratory, Space Flight Inc, Space Infrastructure Foundation, Space Logistics, Space Works, Starfish Space, Surrey Satellite Technologies Limited, Ten One Aerospace, Tethers Unlimited Inc., Thales Alenia Space, True Anomaly Inc, Valor Robotics. Moreover, CONFERS[18], a Consortium for Execution of Rendezvous and Servicing Operations, has collected more than 60 such enterprises and is actively promoting the emerging industry to deal with the threat of orbital debris, not only by de-orbiting, but by recycling, reuse, refurbishment, and enhancement of either defunct spacecraft or spacecraft nearing end of mission.

According to recent studies on the Orbital Debris Removal market evolution between 2022 and 2030[19], the market is segmented into removal, avoidance, and monitoring. The removal segment is expected to account for the largest share of the market, driven by the increasing demand for mitigating the risk of collisions with satellites and other spacecraft. The market is segmented into commercial and government. The commercial segment is expected to account for the largest share of the market due to the increasing number of commercial companies involved in space exploration and satellite launches. North America is expected to account for the largest share of the market. Europe, Asia, and the rest of the world will also grow at a high CAGR.

Orbital Debris Reuse: the most important market to come

As seen above, the Orbital Debris Removal market is already a reality, and growing fast. How much is a real Circular Space Economy (CSE) realistic, and how far is it in the future? CSE will require not only industrially efficient techniques and spacecraft to catch and move large and small debris, yet substantial additional items, such as orbital factories, capable of reprocessing debris, and producing raw materials for further industrial use. Such a development will mark the kick-off of the Earth's orbit industrialization. Of course, the first step on such an agenda is the ODR, and it is well on its road. Yet design and investments in CSE should start immediately too, since it will be the real boom factor, for the new space economy, before and beyond 2030.

The European Space Agency classified Debris objects via a decision tree, 'Reuse' and 'Scrap Material' scenarios. Leonard and Williams, in their paper "Viability of a circular economy for space debris"[20], prospect that a high-end estimate for reuse shows a net value of $1.2 trillion. It is worth observing that such a figure is higher than the foreseen volume of $1 trillion attributed to the space economy within 2040 or earlier by several specialists. It is reasonable to think that, if developed, the CSE-generated $1.2 trillion would add to the $1 trillion of the space economy. And likely, the combined outcome of the orbital industry and CSE will be more than the mere sum; therefore, the forecast of $3.5 trillion for the space economy in 2040[21] will not be unrealistic at all. The development of in-orbit services will be crucial to solve the orbital debris problem. A future circular economy for space may be financially viable, with potentially beneficial consequences for risk reduction; resource efficiency; additional high-value employment; and climate-change knowledge, science, monitoring, and early warning data.

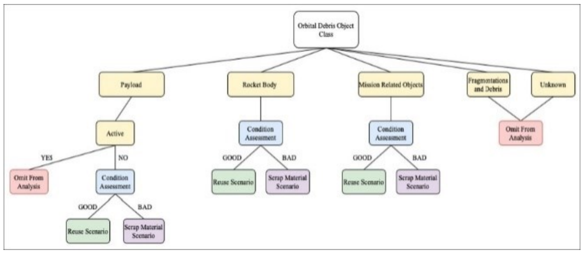

Figure 5 ESA Orbital Debris reusability classification

As we can see, in the above-mentioned study, small debris is excluded from consideration. Though dangerous enough, small debris is hard to collect, and therefore very hard to include in industrial business plans. NASA considers two methods for Remediation of Small Debris[11]: Pulse Lasers (from Earth's surface or in orbit), and Physical Sweeper in Orbit. While laser techniques seem only targeted to change the debris' orbit or to de-orbit them, the Sweeper concept concerns big absorbent pads, that can capture small objects or meaningfully reduce their velocity. That could maybe allow to collection of big quantities of debris, a necessary precondition for any treatment. However, the above referred NASA's study only considers the recycling option for large debris, by converting its material into propellant. Several benefits are associated with the recycling solution by Colvin et Al, yet they don't seem to appreciate the big impulse to orbital industrialization as a deciding factor, that could, alone, boost the growth of the orbital debris remediation industry and, subsequently, an accelerated solution to the orbital debris issue.

We strongly recommend NASA, ESA, and the main space agencies, promote orbital debris recycling toward the space industry, and the associated research, to assist the emerging market in its development.

<u>Considering Orbital Debris and NEOs as In Situ Orbital Resources (ISOR)</u>

In this article of 2017, "Seven million and a half kg of gold in orbit"[22], the author of this paper, A. V. Autino, made some rough calculations. About 7,5 million kg. man-made things were estimated (in 2017) to orbit planet Earth, including operative satellites, dismissed ones, and trash. At the average cost of 20,000 USD/Kg, such orbiting materials cost about 300 $bn, just to be launched to Earth orbit. Let alone the cost of design, building, and test/integration.

Furthermore, everything orbiting Earth is a bearer of orbital velocity, which is a big danger but also a precious property, a useful Delta-V, i.e. they just need a little more acceleration to move everywhere we might need them to go.

Wrote Autino, in that article: *"... waste [on Earth] constitutes an environmental tragedy only for those who have not yet decided to use it. For those who own good recycling facilities, waste is worth gold! In addition, for the plant owners, the profit is made twice, as it not only produces energy and materials of various uses, but they are paid to receive the waste from those who are not equipped to use them! [...] Did you get the picture, looking down at the ground? Well, now look up. We immediately realize that, with regard to so-called space waste, the whole world is blind, and no companies have yet emerged capable of investing in the facilities needed for the collection, processing, and reuse of this immense orbital wealth. By developing orbiting modular workshops – the experience with the International Space Station is fundamental – we can begin to capture scrap, separate metals from plastic, grind the various components, and extract dust, the "raw" material for 3D printing. What are we waiting for?"*

Orbital Debris, as well as Near Earth Objects, should be considered In Situ Orbital Resources (ISOR), for all potential uses.

<u>Products from Orbital Debris</u>

A rough list of products obtained by re-processing orbital debris shall take into account the possible progression of orbital and cislunar industrialization process, that will go ahead according to the downsizing of the Earth-orbit transportation cost. Not only space industry will develop copying that curve, yet space tourism and moon settlement, too at least. Orbital workshops will go through an evolutionary process:

- from mitigation to remediation
- from deorbiting to gathering
- from mere expenditure to investment and profit
- from small compact service satellites to more complex settlements, providing maintenance and more sophisticated services
- from debris elimination to recovering
- from debris destruction to reprocessing and reuse
- from merely simple automated to manned complex infrastructures

Following the above evolutionary process, we can envisage a range of progressive product classes, which will become feasible and profitable with the advance of the evolutionary steps:

1. The first product will be **Risk Mitigation**. This is based on a simple question: what would be the cost, and the loss of profit, for the satellite producers and customers, if the risk posed by an increasing debris population in orbit will not be mitigated? Selling this product to the proper clients will allow the consolidation of proper technologies for risk mitigation, such as dismissed satellite de-orbiting, new debris avoidance, anti-collision techniques, and first-gathering techniques.

2. **Rockets' Upper Stages** and fuel tanks recovery will represent a great saving, for the construction of new orbital infrastructures, such as space hotels, research stations, and simulated gravity orbital stations. Tones of aluminum can be recovered from the upper stages of Ariane 5[23]. With such material, it will be possible to build large parts of a lunar station, for example, walls, power lines, or heat storage systems. Being the materials collected in orbit, transporting them to the Moon will just require small propulsion units, which can be launched at moderate costs. Over 50 billion Euros can be saved in transport costs.
3. Producing **Fuel from Metals** is the next step. Thousands of tons of aluminum in orbit can be very profitably recycled to produce propellant for rockets[24]. While the 1st key milestone in reducing the cost of any mission is rockets reusability, producing propellant in space will be the 2nd one. After downsizing the Orbit transportation cost from $54,000 / Kg to $1,000 / Kg, producing fuel in space will bring the space transportation cost under $100 / Kg, paving the way to further progress.
4. Producing **Powders for 3D Printing**. In a more advanced stage of orbital industrialization, orbital manned versatile multi-products workshops will directly decompose space debris in their different components, plastic, metals, and electronic components. Duly reprocessed, each kind of material will then be available as input materials for 3D Printing. Orbital factories will then provide space-made products to space customers and to Earth ones as well.

Orbital space vehicle garages, in-orbit rescue/lifetime extensions, and scrap dealer business: opportunities for human-robotic infrastructure

Several business opportunities exist, related to the theme of orbital debris mitigation and reduction. They can be summarized as in-space servicing, including satellite and spacecraft maintenance, re-fuelling, refurbishing, and relocating; garages to host space vehicles; scrap dealers, and demolition yards. All of the above activities are highly synergistic with the orbital debris recovery and reutilization grand process. Primary input materials for the construction of such infrastructures may be big objects in orbit, like rockets' upper stages and dismissed big satellites. In order to recover this kind of object proper technologies should be developed, to reduce their rotating and basculating motion, facilitating to grip them and bringing them to the re-processing plant.

Inflatable and chemically rigidizable technologies may contribute to setting up such infrastructures. Large inflatable lightweight hangars may simply help to regroup objects in a closed space, avoiding possible drift and dispersion in space. Hangars made of thicker inflatable walls may also protect from cosmic radiation and micrometeorites, allowing human technicians to work inside. Working in relatively large enclosed spaces, though in absence of gravity and of atmosphere, allows people a major freedom of movement, avoiding being tied up. Psychological conditions will be greatly enhanced too.

Robotic systems are of great relevance, to supporting all human activities in such environments. Grabbing and manipulating objects in space and inside hangars can be done by means of proper robotic machines, properly propelled.

The role of automated robotic systems will also be essential in the various processes of debris re-processing and new component production.

Some of these services in orbit are already active, though fully robotic, so far. Mission Extension Vehicles (MEV), are provided by Northrop Grumman[25], in the frame of what they called Space Logistics. "SpaceLogistics currently provides in-orbit satellite servicing to geosynchronous satellite operators using the Mission Extension Vehicle (MEV)™ which docks with customers' existing satellites providing the propulsion and attitude control needed to extend their lives. This enables satellite operators to activate new markets, drive asset value and protect their franchises."

Mission Robotic Vehicle (MRV) is a similar service provided by DARPA[26]. The public-private partnership between the Pentagon's far-future research agency and Northrop Grumman's SpaceLogistics is developing a robotic vehicle to physically repair ailing satellites. MRV will begin operation in 2026, it will remain in GEO for 10 years, visiting typical 2000 Kg satellites, and installing on them the Mission Extension Pods (MEP), elongating so of 6 years the life of the satellite.

Satellite refueling is a nearly active service, as well. OrbitFab is currently offering a refueling service to satellites in orbit[27], to supply hydrazine and most common fuels to orbital clients. Satellites, explains the corporate's website, dedicate up to 75% of mass to propellant. By refueling, satellites can not only extend operative life, yet also augment their capabilities of maneuvers, relocation, collision avoidance, on-demand operations, and secondary missions.

For the sake of an advanced satellite and spacecraft maintenance practice, standard subsystem exchange techniques should also be implemented. Such methodology will allow for elongating the operative life of any space system in orbit, reducing the possibility of producing new space debris. At the same time, it will boost the process of orbital industrialization.

Of course, the existing or near-to-exist infrastructures only make use of resources uploaded to orbit from Earth's surface and are fully automated. A true jump upwards will be done when fuel will be produced in space, by reprocessing orbital debris and processing lunar and NEO's raw materials.

The technology of space debris rendezvous, capture, steering and shepherding, central orbital garage repair or disposal

There are technical difficulties unique to approaching and gripping space debris. Large orbital wreckages generally consist of used rockets or non-operational satellites that have finished their missions. They have no active subsystems nor operational communication devices and have lost their attitude control capability, which could help rendezvous. For these reasons, a debris-removal spacecraft needs navigation technology, and the ability to estimate the accurate position and attitude of debris, prior to rendezvous. Moreover, the spacecraft will have to approach and capture rotating debris, which is far more difficult than capturing a stable target. JAXA conducted studies on this subject[28] and is developing technologies to overcome those difficulties. The most critical issue is to get the object steady to be recovered, stopping rotations, tilting, tumbling, and basculations. That can be done by means of truster's plumes (see Figure 6).

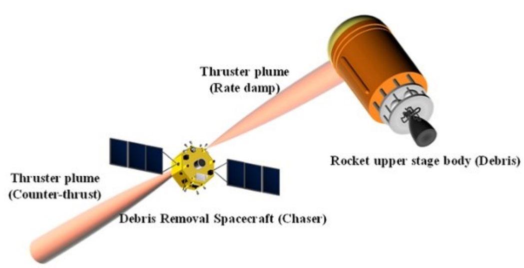

Figure 6. Large debris damp by thruster plume impingement

NASA has introduced the ADRV[29], to remove large debris from LEO, such as spent rocket bodies and dismissed satellites. The concept yields a single use, low-cost, lightweight, high mass fraction vehicle that enables the removal of large orbital debris (1000 - 4000 kg mass, 200 - 2000 km altitude, and 20 98-degree inclination). The ADRV performs rendezvous, approach, and capture of non-cooperative tumbling debris objects, maneuvering of the mated vehicle, and controlled, targeted repositioning or deorbit of the mated vehicle. Up to eight ADRVs can be launched in a single payload, enabling high-impact orbital debris removal missions within the same inclination group. Three key technologies were developed to enable the ADRV: 1) The spacecraft control system (SCS), a guidance, navigation, and control system that provides vehicle control during all phases of a mission; 2) The debris object characterization system (DOCS) characterizes movement and capture of non-cooperative targets; and 3) The capture and release system (CARS) allows the vehicle to capture and mate with orbital debris targets.

What can be done, once a large debris was captured and gripped by a properly designed and constructed "chaser" vehicle? At least 3 alternatives:

a) to de-orbit the wreckage, forcing it to re-enter the atmosphere
b) to bring it to a central orbital garage, orbital yard, or workshop, where it can be disassembled and its parts reprocessed to get new raw materials or recombined with other parts, to get a semi-worked part of an infrastructure
c) to bring it to a parking area, in Earth or Lunar orbit, or in a Lagrange point, for future use

Any of the above destinations, or other possible ones, foreshadows the need to develop interorbital transportation cargo systems, big enough to move medium and large objects among different Earth orbits and to Cislunar space.

Chinese scientists have apparently developed a new kind of magnetized coaxial gun that can generate magnetized plasma rings to move stuff at a distance without physical contact[30]. Conceived for military use, the device could prove revolutionary for many industries, if proven viable, including debris capture and remediation.

THE FIRST STEPS

Orbital debris classification

Achieving a better analytical classification and terminology is key: it is evident that small debris, a few millimeters large, pose quite different problems, respect big wreckages, from all points of view, collection techniques, stocking, processing, legal.

General classification

Space debris is to be classified based on its orbital parameters, size, mass, spin, albedo, and spectral characteristics allowing to determine the debris material type.

Chemical classification

In their paper of 2004, Li Chunlai and his colleagues propose a concept of chemical classification for man-generated orbital debris[31]. Generally, space debris is classified as large, medium, and small debris pieces based on their sizes. The large debris piece is easily cataloged, but medium to small debris pieces are very difficult to track and also quite different in damage mechanisms from the large ones.

A scheme of chemical classification of space debris may help to conceptualize different techniques for recovering and possibilities of reuse. Artificial orbital debris is divided into seven types, which are: polymers, non-metal debris, metals and their alloys, oxides, sulfides, and their analogs, halides, and carbides. Chemical classification of space debris is very useful for the study of the chemical damage mechanism of small debris pieces and also is of great significance in constraining the origin and source of space debris and assessing their impact on spacecraft and human space activities.

Business-oriented design of orbital debris recovery technologies and methodologies

Beyond the obvious consideration, that proper recovery and process technologies and methodologies should be identified for each type of debris, we shall observe that recovery technologies in the progress of design and experimentation should be quickly oriented towards their application for business and industrial activities.

Industrial requirements should be considered from the very initial phases of the project, even before any conceptual design and concept proof testing. Industrial requirements – vs. conceptual proof requirements – necessarily include quantitative aspects. By way of example only, a couple of cases. As far as big derelicts are concerned, the size and mass have great relevance, in conceiving capture methodologies and suitable machines to do the job, namely considering the issue of pairing the pivoting and tilting of the object to be gripped and secured.

As far as small objects are concerned, the problem of dispersion in space may be the most relevant to overcome. For a demonstration project, it would be enough to catch a small number of objects. For industrial purposes, any technique would be void of meaning, if it cannot catch big quantities of objects.

The needed evolution of Space Law and Space Governance

Who owns space debris? Article VIII of the Outer Space Treaty[32] provides that each State retains ownership and control over objects launched into space that are registered on its registry: "Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth."

The authors of this paper "The Economics of Space Debris in Perspective" propose a view of the Return Of Investment in Space Debris mitigation and remediation as avoidance of huge losses due to a possible future inability of Earth Orbit after a Kessler syndrome following a growth of space debris out of control. Curiously, the paper doesn't mention at all the reprocessing and reutilization of orbital debris This note about existing space law points out its backwardness, and consequent need to be updated: *"[…] there are numerous legal and geopolitical challenges when exploring active space debris removal. First, from a legal point of view, the Outer Space Treaty (1967) and the Liability Convention (1973) establish a strong property ownership regime of "space objects", which states that no nation may salvage, or otherwise collect, the space objects of other nations that are in space without the formal consent of the object's registered national owner. The retrieval of debris would involve sharing potentially sensitive data about the object's design that could involve national security, foreign policy, intellectual property rights, etc. 'Reverse engineering' could also be possible. From this perspective, countries would realistically be limited to removing their own satellites."*[33]

High Space Law (borrowed from Maritime Law)

Maritime tradition holds in high regard compensating private parties who rescue vessels & prevent destruction: Phoenicians, Greeks, & Romans rewarded "salvors" for rescuing ships & cargo[34].

Several studies suggest that maritime law could be added or integrated into the Space Law[35], in order to remediate many lacks of the Outer Space Treaty. As far as orbital debris is concerned, the marine salvage (right of recovery of the shipwreck at sea) could be usefully applied to dismissed satellites, spacecraft, and spacecraft parts in orbit.

Several similarities are detected between maritime and orbital environments, from the point of view of orbital debris removal, salvage, and use (Salvage lessons from international marine salvage tradition and law)[36]: creation of debris consequent to catastrophic failure over land, space tourism will turn out to be more like cruise ship tourism, space activities sometimes resemble specialized maritime activities, and the commercial space-launch industry resembles the maritime sector much more than the air-transport sector. In a nutshell, any saver should have the right to recover big wreckages, as this right is granted in the sea, by maritime law. The above-referred NSS's position paper proposes the creation of a Space Salvage Entity (SSE), the governing council of which to be composed of State Parties to the OST. The SSE should be endowed with several capabilities, including (among other powers) setting annual goals for the reduction of space debris, and issuing "Kessler Credits" to commercial operators corresponding with actuarial risk, which would reflect on liability risk; to take jurisdiction, control, and liability for all

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unclaimed and unregistered objects; to acquire registration and jurisdiction and control and assume liability risk for derelict objects; to set bounties for the removal or salvaging of orbital debris; to license debris removal operations authorized under its charter; to hold auctions for removal or salvage.

Toward a modern Space Governance: an Orbital Debris "Cap and Trade"

The creation of a Space Salvage Entity would inaugurate a new age of modern governance in the geo-lunar space region. An SSE will open the way to an international/multilateral market-based system, to reduce creation and spur the clean-up of orbital debris by creating a financial incentive to do so (the trade), and a limit (the cap) to the allowed polluting operations. That would also stimulate a more decisive growth of the private sector holding the mission of repairing and enhancing satellites, to elongate their operative life by refueling and maintenance. Such an industrial sector is already in place[37].

We also retake and share this recommendation, already advanced to COPUOS in 2018 by the unforgotten David Dunlop[38]: eventually convene an International Space Anti-Dumping and Salvage Convention, informed by customary international law & maritime tradition & law to codify & refine what has evolved from actual orbital debris clean-up practices over the years.

Encouraging cooperation among responsible entities of space pollution (nations), research entities, and the space industry

Proposing a business approach to orbital debris doesn't mean fully delegating the effort to private industry. The main space pollution nations hold a huge responsibility for the current situation, therefore they are expected to contribute to the solution, and transformation of the risk in an opportunity. As a first commitment, the space-polluting nations should keep on developing the necessary scientific and technological research, and possibly accelerate it.

Evolving the space law is fundamental, to encourage and facilitate cooperation among the growing number of space-faring Nations and commercial operators, in order to revert the growing curve of orbital debris, and kick off a profitable orbital ecosystem, based on a circular economy.

We strongly recommend NASA, ESA, and the main space agencies, promote orbital debris recycling toward the space industry, and the associated research, to assist the emerging Orbital Debris Remediation and Recycling market in its development.

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