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RESULTS FROM THE H2020 ReDSHIFT PROJECT: A GLOBAL APPROACH TO SPACE DEBRIS MITIGATION

A. Rossi[a]*, C. Colombo[b], J. Beck[c], J. Becedas Rodríguez[d], F. Dalla Vedova[e], V. Schaus[f], A. Francesconi[g], S. Walker[h], K. Tsiganis[i], R. Popova[j], T. Schleutker[k], I. Holbrough[c], H. Stokes[l], E.M. Alessi[a], I. Gkolias[b], Y. Kim[j], G. Schettino[a], D.K. Skoulidou[i], E. Stoll[f], F. Letterio[m]

[a] *IFAC-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy,* a.rossi@ifac.cnr.it
[b] *Politecnico di Milano, Milano, Italy*
[c] *Belstead Ltd., UK*
[d] *Elecnor Deimos Satellite System, Spain*
[e] *LUXSpace, Luxembourg*
[f] *Technische Universität Braunschweig, Braunschweig, Germany*
[g] *Università di Padova, Padova, Italy*
[h] *University of Southampton, UK*
[i] *Aristotle University, Thessaloniki, Greece*
[j] *University of Cologne, Germany*
[k] *DLR, German Aerospace Center, Germany*
[l] *PHS Space Ltd., UK*
[m] *Deimos Space, Spain*

* Corresponding Author

Abstract

The ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies) project has been approved by the European Community in the framework of the H2020 Protec 2015 call, focused on passive means to reduce the impact of Space Debris by prevention, mitigation and protection. The main innovative aspects of the project concern a synergy between theoretical and experimental aspects, such as: long term simulations, astrodynamics, passive de-orbiting devices, 3D printing, design for demise, hypervelocity impact testing, legal and normative issues. After more than two years of work, the project is approaching its end. The main expected output are almost complete. The first complete dynamical mapping of the whole space, from LEO up to the geostationary orbit, was performed, looking for "de-orbiting highways", i.e., preferential escape routes to speed up the disposal of spacecraft at the end-of-life, both with and without the use of area augmentation devices. The first prototypes of 3D-printed spacecraft (and of specific spacecraft parts) were produced and extensively tested. A number of innovative Design for Demise tests were performed both on 3D-printed samples and on traditional space hardware. Hypervelocity and radiation tests were completed on a number of 3D-printed samples to understand their suitability for the prototype spacecraft. A software tool, encompassing the main project findings and allowing a preliminary design and definition of a debris compliant mission (in terms of de-orbiting strategy, shielding, demising, etc.), is now completed and will soon be made publicly available on the website of the project. The legal and normative implications of the project's findings (e.g., their potential impact on the current mitigation guidelines) is being explored. The paper presents an overview of the ReDSHIFT results obtained so far, in an effort to highlight the holistic approach of the project covering different aspects of the space debris mitigation field.

1. Introduction

The impact of debris on the space activities has to be reduced by adopting a global strategy able to address the problem from different points of view, from the very beginning of the planning of a space mission. The choice of the orbit, of the spacecraft bus, of the spacecraft power system and propulsion, are all aspects that influence, and have to be optimized, having in mind not only the goal of the mission but also the minimization of the "environmental" impact of the spacecraft, in particular at its end-of-life. The space debris related aspects can be summarized in terms of: prevention, protection, mitigation and regulation. All these aspects are considered within the Horizon 2020 project ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies). ReDSHIFT has been funded by the European Union in the framework of the PROTEC Call of Horizon 2020 (see http://redshift-h2020.eu/).

The main goal of ReDSHIFT is to tackle the space debris issue from a global perspective using expertise from several different fields: long term simulations of the space debris environment, astrodynamics, 3D printing, design for demise, protection and hypervelocity impact testing, legal and normative issues.

As a preliminary step, a thorough analysis of the currently adopted mitigation measures was performed to highlight their benefits and, possibly, their deficiencies in some aspects. This analysis was assisted by a number of simulations of the long term evolution of the space debris environment showing the overall effects of these measures in a quantitative way [14]. In the following sections the most recent results of the project will be briefly described. In Sec. 2., a comprehensive study of the orbital dynamics in all the circumterrestrial space allowed us to identify stability and instability regions with the aim of exploiting them to find preferential routes (we called them "de-orbiting highways") minimizing the energetic requirements for the operators, thus improving the applicability of the disposal maneuvers. Describing the more experimental part of the project, in Sec. 3., the novel possibilities offered by the additive manufacturing (3D printing) technology were exploited to produce prototype spacecraft and specific parts related to the debris mitigation issues, such as, e.g., the shielding (see Sec. 3.1), a sail canister, etc. The test performed on these samples, including design for demise, hypervelocity and radiation test are described in Sec. 3.1 and 3.2. The final outputs of the project will include also a software, described in Sec. 4., summarizing the theoretical and engineering findings, allowing the design of a space debris compliant mission (e.g., by suggesting the disposal trajectories and the technologies needed to achieve them, the best shielding opportunities for a given spacecraft and the possibility to produce it with additive manufacturing, etc.). Last, but not least, all the experience gathered will be applied to the analysis of the normative related to space debris, in an effort to propose, to the proper forums new, improved mitigation practices and rules (Sec. 5.).

2. Dynamical mapping

As also shown by the long term simulation of the environment performed within the project [14], the disposal of objects after the end-of-life is one of the most important mitigation measures needed to reduce the growth of space debris in the forthcoming years. In order to facilitate this action it is important to identify stable and unstable regions in the phase space where the objects could be moved to exploit either long term "graveyards" or, possibly and preferentially, faster escape routes. To this purpose, a dynamical mapping of the circumterrestrial space was performed within ReDSHIFT.

The whole space, from LEO up to the geostationary orbit, was divided in a fine grid in the orbital elements space. The non-uniform grid is denser were the population of objects is more abundant. About 20 millions of initial conditions were propagated, with three different orbital propagators, having similar dynamical models expressly tailored to the explored orbital regime, but different underlying computational engines. All the orbital propagations were repeated twice: once assuming for the test object an area-to mass ratio, A/m equal to the standard satellites ($0.012\ \mathrm{m}^2/\mathrm{kg}$) and then assuming an augmented A/m ($1\ \mathrm{m}^2/\mathrm{kg}$, thus simulating the presence of some sail). In both cases the reflectivity coefficient c_R was considered equal to 1 and the drag coefficient c_D equal to 2.1. The output of these massive orbital propagations was stored in terms of maps displaying, e.g., the lifetime or the maximum eccentricity growth for all the orbits during the 120 years time span of the propagation. Examples of the maps obtained, for the different orbital regimes are shown in Figs. 1-3.

All the maps produced can be found in the web-

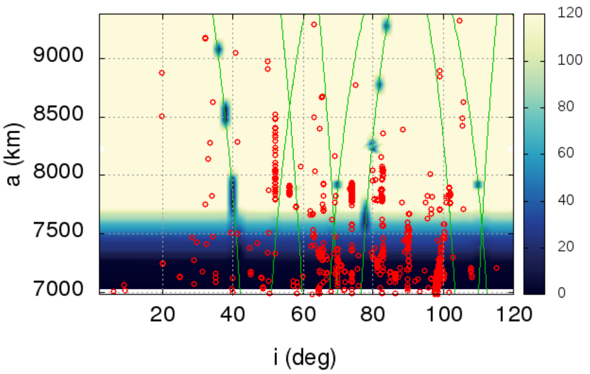

Figure 1: Location of the dominant resonances determining the long-term behavior in LEO (green lines). The color map shows the residual lifetime, as a function of the initial inclination and semi-major axis, computed in 120 years for an object with A/m = 1 m^2/kg, starting from e = 0.001, $\Omega = 0°$ and $\omega = 0°$. The small red circles show the location of the satellites (active and non active) from the MASTER2009 population.

site of the project (http://redshift-h2020.eu) and the theoretical analysis of the results obtained in the mapping can be found in [3], [12], [18], [19], [7], [17] and cannot be repeated here for lack of space.

Fig. 1 shows the location of the resonances determining the long-term behavior in LEO [1], superimposed on a residual lifetime map. The objects considered start from initially circular orbits and have an area over mass ratio $A/m = 1$ m^2/kg. The dark blue regions at the bottom of Fig. 1 correspond to residual lifetimes compliant with the 25-year rule [11]. The small red circles show the location of all satellites (both active and non-active) present in the MASTER 2009 population. It can be noticed how many of the satellites now in space lie in orbits quite close (in terms of orbital elements) to some of the resonances. It could be argued that some specific missions, populating the long lifetime yellowish regions, might be preferentially steered, already in the design phase, towards the resonance spots, in order to benefit from the augmented disposal speed granted by the unstable resonant orbits, saving the propellant needed to move the satellite toward the entry into the resonance, at the end-of-life. Of course such steering should be leveraged with the mission purposes and might sometime be unfeasible. Nonetheless, this issue will be further explored also in the framework of the legal aspects of the project (see Sec. 5.).

On the same line, maximum eccentricity maps were produced for the MEOs and the main resonances in that region were highlighted [12]. Fig. 2 shows that there exists indeed the possibility to deorbit from the Global Navigation Satellite Systems (GNSS) altitude by exploiting the natural growth of eccentricity of the unstable orbits. Whereas the time required for this deorbiting exceeds the classical 25-year timespan, it is worth stressing that the actual time spent in the LEO protected region by a spacecraft re-entering from MEO in an elliptical trajectory is just a small fraction of its residual lifetime.

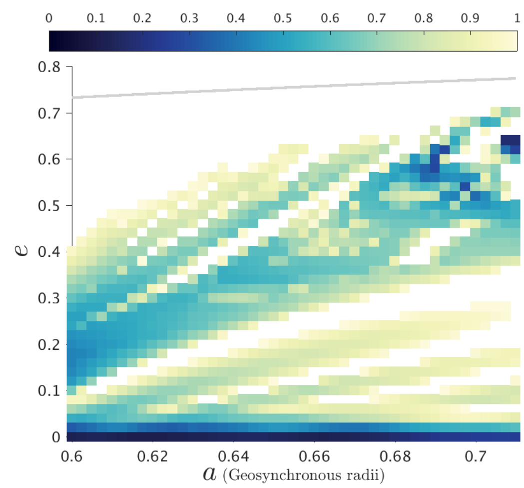

Figure 2: Maximum eccentricity map for medium Earth orbits with inclination $i = 56°$, in the GNSS region. The white regions indicate that the eccentricity needed to re-entry into the atmosphere is reached within 120 y. An $A/m = 1$ m^2/kg is assumed.

For the GEO region, both the geosynchronous equatorial orbits and the highly inclined geosynchronous orbits (e.g., used recently by the Chinese Compass system) were explored. In the former case, whereas natural re-entry solutions cannot be found, e.g, Fig. 3 shows the maximum eccentricity variations reached by a spacecraft starting from an inclined GEO, mainly due to lunar perturbations [7]. A significant increase in the orbital eccentricity can be noticed for these cases, opening the way to possible disposal manoeuvres, even from these high Earth

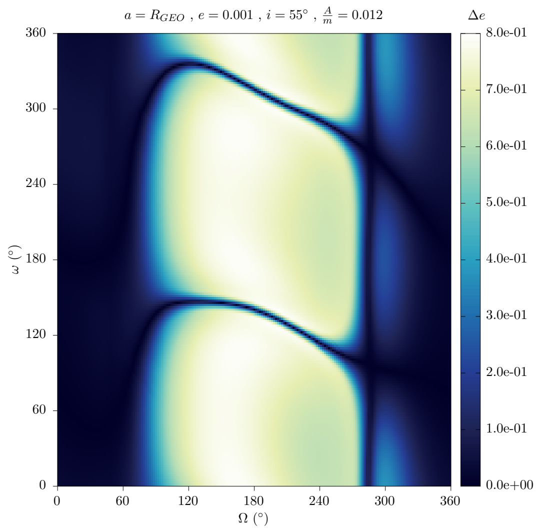

Figure 3: Maximum variation of eccentricity for several initial orientation of the GEO orbit with respect to the equator (initial inclination equal to 55°, initial eccentricity equal to 0.001).

orbits.

Building on the knowledge acquired with the dynamical maps, the end-of-life disposal manoeuvres needed to exploit the natural dynamics, were computed (e.g., [16], [15] for the LEO part). The natural dynamics is enhanced via impulsive manoeuvres, solar and drag sailing and a combination of manoeuvre and solar and drag sailing. The end-of-life manoeuvre requirements need to be designed based on mission characteristics such as the available on-board propellant and the area-to-mass ratio of the satellite. Exploiting the developed methods, it is possible to determine the optimal re-entry or graveyard orbit, given an available ΔV on board the satellite. Slightly different design strategies are followed for the LEO, MEO and GEO environment. The strategy followed for disposal in LEO consists in computing the possible displacements in (a,e,i) for a given ΔV provided in input, in order to identify the most suitable final orbit that can be achieved with that ΔV. The maximum ΔV considered for the simulation is the one corresponding to a direct re-entry manoeuvre down to 80 km of altitude. In this way, all the possible target orbits are selected and, among them, the one that will naturally evolve toward re-entry in a time less than 50 years are chosen. For all these cases, the required ΔV is computed as a single burn manoeuvre in case the two orbits are intersecting.

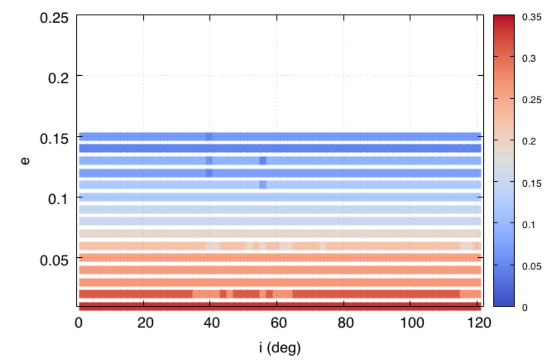

Figure 4: Example of solutions for re-entry from low-Earth orbit, the colour bar represents the ΔV requirements, in km/sec. The figure shows the minimum-cost re-entry solutions, $a_0 = R_E + 1520$ km.

Moreover, as mentioned above, a solar radiation pressure-augmented case, considering an A/m of 1 m^2/kg, was studied. In this case the corresponding resonant inclination bands, presented in [1] and [3], are targeted. This corresponds to a two-phase deorbiting strategy: a relatively small manoeuvre is performed to reach a resonance where the atmospheric drag or the solar radiation pressure can then be exploited to re-enter by means of a passive stabilised sail [16].

For the MEO and GEO region a similar design strategy was devised: given the initial post-mission orbit and the maximum available ΔV on-board the satellite, the reachable orbital element domain is computed via a single manoeuvre. From all the reachable orbits, we exclude orbits in GEO protected region and a MEO protected region, that was defined in ReDSHIFT around the GNSS satellite constellations. The required manoeuvre sequence to reach each one of this target orbit is computed. In the MEO case, a transfer with 1 and 2-burn manoeuvre given at the characteristic points of the orbit (i.e. apogee, perigee, nodes) is performed. In the GEO case, the optimal transfer between the last operational orbit and any of the possible target orbits is computed with a 2-burn manoeuvre, through the Lambert problem solved on a grid of initial geometrical configuration and time of flight. The best results are chosen by representing the Pareto front solutions in terms of the minimum ΔV and re-entry time.

Fig. 5 shows an example of Pareto front solutions for re-entry orbit of graveyard orbit started from a GEO orbit [8]. For the conventional GEO ring, graveyard solution exists and their stability can be measured in terms of the maximum variation of eccentricity in 120 years. For higher initial inclinations, instead, re-entry is possible in less than 120 years as it is shown in the Pareto front solutions of Fig. 5. The quality of a re-entry solution can be represented in terms of ΔV to reach the natural re-entry corridor and the re-entry time. An example of the Pareto front solu-

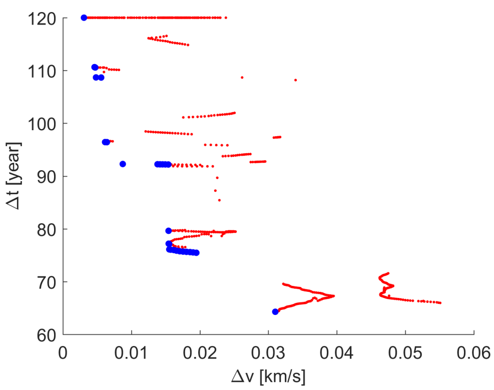

Figure 5: Example of solutions for re-entry from GEO [8]. Pareto front of re-entry solutions from inclined GEO orbit.

tions for re-entry orbit from MEO is instead shown in Fig.6. For all 1-burn (dark triangles) and 2-burn Hohmann (light grey point) manoeuvres found. The blue/red curve is the Pareto front. A number of possible solutions with $\Delta V \leq 200$ m/s and $T_r \geq 60$ years can be seen. Within the ReDSHIFT project the disposal via solar and drag was studied too, with particular emphasis on the use of solar sailing that allow deorbiting for orbit with perigee higher than 600 km. Conventional active solar sailing for deorbiting aims at maximising the cross area of the sail perpendicular to the spacecraft-Sun direction when the spacecraft is moving towards the Sun, while the sail area is minimised when the spacecraft is flying away from the Sun. A second strategy keeps the reflective surface always oriented towards the Sun and control it through passive stabilisation. A third novel strategy for solar sailing has been proposed in the ReDSHIFT project, named as *modulating solar sailing*. The sail area is oriented perpendicular or at feather with respect to the Sun, with a period of about six months so that the eccentricity of the or-

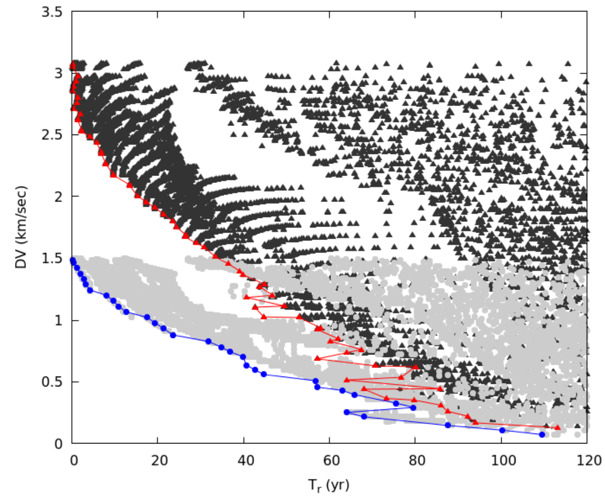

Figure 6: Map of the ΔV needed to deorbit a typical Galileo spacecraft versus the time T_r needed to reach the re-entry. for all 1-burn (dark) and 2-burn Hohmann (light grey) maneuvers found. The blue/red curve is the pareto front. A number of possible solution with $\Delta V \leq 200$ m/s and $T_r \geq 60$ y can be noticed.

bit is constantly increased until re-entry. It has been demonstrated that, with such a sail control, satellites up to the MEO region can be deorbited with a small sail area and a deorbiting time less than 25 years. A large number of maps were produced showing the requirements (in term of sail area), as a function of the starting orbital elements, for deorbiting in 25 years using the different solar radiation pressure strategies.

3. Additive manufacturing

The starting point for the design of the spacecraft is the definition of the mission requirements. The selected purpose of the spacecraft is a LEO Earth Observation multi-spectral mission on Sun Synchronous orbit. An 8U CubeSat (200 x 200 x 200 mm) of 8 kg was selected.

The 8U CubeSat design was provided by Elecnor Deimos Satellite Systems (EDSS) to act as a baseline configuration to study the potential application of additive manufacturing to small satellite primary structures [4]. Whereas some of the sections of the spacecraft are currently being 3D printed, it is worth stressing that the first detailed design is mostly based on traditional manufacturing techniques (see the top panel of Fig.8). In particular, as shown in the bottom panel of Fig. 8, currently three similar prototype spacecraft were produced: a 3D printed satellite in plastic, an aluminum spacecraft with plates produced with traditional milling and later assembled and an hybrid spacecraft with some 3D-printed parts later assembled with CNC milled aluminum plates. After the first round of testing (vibration, radiation, etc.) the design will be updated and a more advanced exploitation of the additive manufacturing techniques will be explored and applied.

Preliminary analysis and tests were already done to investigate the transition from conventional machining to 3D printing of the selected 8U CubeSat satellite (e.g., Fig. 7). This constitutes a baseline

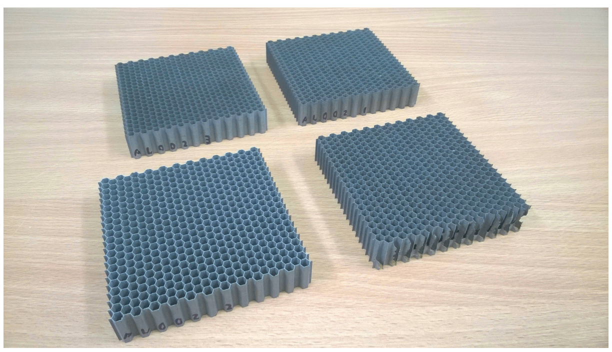

Figure 7: 3D printed samples of aluminum prototypes with 200 micron core thickness.

study for the application of additive manufacturing to small spacecraft structures. Important manufacturing issues and "lesson learned" arose already in the first print of an 8U CubeSat panel oriented vertically, indicating need to redesign any vertical structure specifically for Selective Laser Melting (SLM) production. In addition, the holes quality has been proven to be poor and not acceptable. Finally, a significant deviation of the structure was observed at the corners, which does not meet the requirements for assembly. On the basis of the test print in the subject, the following recommendations for 3D printing were derived:

- The only feasible orientation to manufacturing the satellite panels designed for Computer Numerical Controlled (CNC) construction would be flat against the print plate. This implies ensuring that the panel geometry aligns with the specific 3D printer plate, which varies between machines and manufacturers. This also implies that none of the panels can be integrated together in the manufacturing stage.
- 3D printing allows for great design freedom and CNC milling features should be abandoned totally. As a consequence the actions to be taken are:
  - Implement mesh structure;
  - Reduce the mass to a minimum;
  - Minimize the required post-manufacturing;
  - Redesign the structure.
- The component must be designed to minimise the amount of support structure required during the printing process. As a consequence:
  - Overhang structures must be avoided;
  - Sharp edges must be avoided;
  - Suitable build angles must be selected.
- Holes must be avoided in the printing process and must be post-manufactured to allow the required positional precision and tolerances. As a consequence:
  - Holes could be included but only with the axis of the hole aligned in the print direction, not oriented parallel to the print plate.
  - Small holes must be avoided.

The preliminary results suggested a suitable 3D printing design optimization strategy, which will be explored in the next phase of the project. In particular, the design will be optimized through the following actions:

1. Additive manufacturing must be used at its potential, abandoning the idea of conventional designs suitable for subtractive manufacturing, i.e. CNC milling;
2. The six side panels of the Cube configuration should be simplified by using a two halves strategy, with the objective of reducing the number of fasteners, simplifying the integration process and minimizing the structural mass.
3. The Tray and Mounting bracket will be subject to a topology optimization for mass reduction, which may lead to them being merged into a single component.

We note that further design studies within the ReDSHIFT include the prototype of a 3D-printed sail attachment [9].

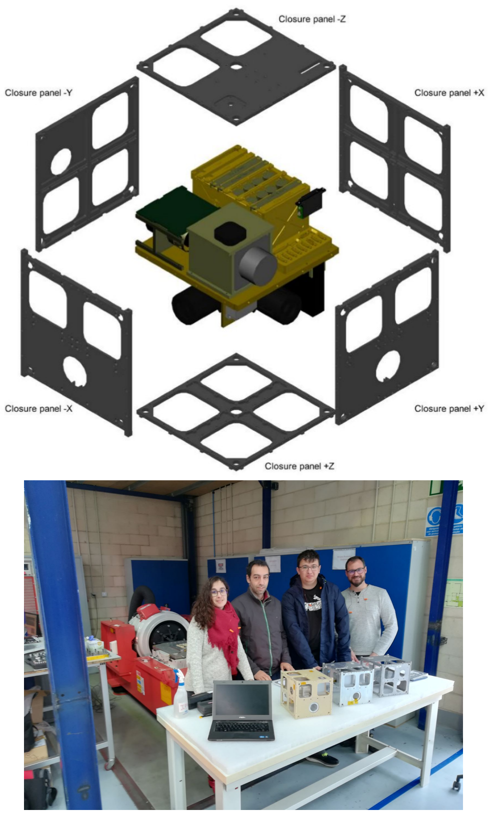

Figure 8: Top panel: RedSHIFT Spacecraft Mechanical Design Concept. Bottom panel: prototype spacecraft produced so far. From left to right: 3D printed plastic spacecraft, traditional aluminum milling spacecraft, hybrid 3D printed-traditional milling aluminum spacecraft.

3.1 *Shielding*

Two baseline shielding concepts were defined for 3D-printing. The shields include a multi-shock panel (MSP), with planar walls of different thickness and variable separation distances, and a single corrugated panel (SCP). Fig. 9 shows the 3D printed prototype of one of the SCPs. The influence of key design parameters, such as overall panel thickness, bumper thickness and spacing, were considered and will be evaluated through hypervelocity impact testing. For the MSP, the default bumper thickness is set to 0.5 mm, but values from 0.25 up to 1 mm were explored. The rear wall thickness in the range 1.0 mm to 3.0 mm is realistic for most equipment, and an intermediate value of 2.0 mm was chosen for the first phase of investigations. Different stand-off distances between the walls in the MSPs were assumed, from 1.5 cm up to more than 10 cm. Two additional concepts were also anticipated, i.e. a double corrugated sandwich panel and a hybrid multi-layered panel with single corrugated bumper. These will be further investigated based on the results of the first testing phase. As a complement to this work, an impact risk analysis was performed using PHS's SHIELD3 model [20] to provide a preliminary evaluation of the shielding performance of the MSP and SCP designs. About 700 simulations were run to estimate the probability of penetration of each panel type when it is applied to different faces of a notional spacecraft. The designed shields appear to be suitable to protect against hypervelocity particles in the 2 mm to 3 mm size range. The simulations pointed out that the stand-off distance between the walls in the MSPs is extremely important for increased protection. Further work will be undertaken to confirm the effectiveness of the baseline shield-panels and their enhanced versions. In particular, with regard to the holistic design of ReDSHIFT, it is desirable if the shield-panels provide comparable structural and thermal performance to standard honeycomb panels whilst offering significant improvements in terms of debris shielding (and re-entry demisability).

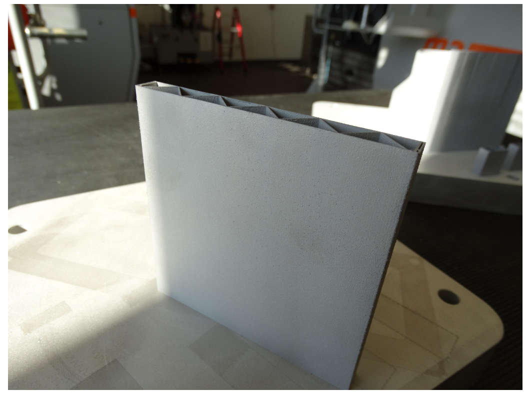

Figure 9: Sample of the 3D printed SCP shield.

3.2 *Testing*

A thorough theoretical and numerical analysis was preliminary performed to identify the state of the art knowledge on the demisability of the materials and components commonly used in the manufacturing of spacecraft. The conclusion was that the current understanding of the phenomenology of the fragmentation and demise processes is limited. Therefore, it is of paramount importance to perform appropriate tests in order to improve the capability of the numerical tools to assist the design process. To this end, a set of destructive tests on spacecraft materials, structures and components (mostly 3D printed) was planned and then performed in the arc-heated supersonic wind tunnel at the German Aerospace Center (DLR). These tests included the first destructive wind tunnel tests ever performed on a complete nano-satellite and on a reaction wheel [5]. The nano-satellite was assembled *ad-hoc* within the project using standard COTS components, while the reaction wheel was manufactured by Rockwell Collins.

From these tests, it has been determined that the failure of aluminum structures is highly dependent upon the behaviour of the protective metal oxide layer, and that this can be catastrophic in nature. The tests on the nano-satellite have shown that the structure can be supported by stainless steel spacers between the electronics cards, and that glass fibre reinforced plastic PCBs are more resistant to melting than had been anticipated. Figure 10 shows some of the CubeSat debris recovered after the tests.

Finally, the reaction wheel test has shown that the connections between parts are critical to the fragmentation and demise processes, as the glued housing separates quickly, well before melt temperature is reached at the joint. It has also demonstrated the importance of radiative cooling, as the flywheel and ball-bearing unit have survived a test at over 800kW/m^2.

Further testing on the 3D printed material and the ReDSHIFT spacecraft were performed in the last few months. Hypervelocity tests were performed at the University of Padova light gas gun [10]. Radiation tests were done in the Padova INFN chamber and the 3D-printed samples showed comparable radiation protection performance to standard honeycomb panels whilst offering significant improvements in terms of debris shielding [10]. Standard vibration tests to verify the compliance of the prototype spacecraft to the usual launchers were performed by EDSS in Spain. All the prototypes produced so far passed the tests. Figure 11 shows one of the aluminum prototype spacecracft on the testing plate.

Figure 10: Remnants from the CubeSat after the D4D test.

4. Software

A software tool available to the scientific community and the public via a web-based interface will be an important deliverable of ReDSHIFT. The ReDSHIFT software is conceived as a tool for spacecraft operators, space agencies and research institutions to design a space debris compliant mission, e.g., by suggesting the disposal trajectories and the technologies needed to achieve them, the best shielding opportunities for a given spacecraft and the possibility to produce it with additive manufacturing, etc. In detail, there will be five interconnected modules:

- a disposal module (based on the results described in Sec. 2.)
- a sail module (based on the results described in Sec. 2.)
- an environment projection module, allowing the computation of the flux and collision probability over a target orbit
- a design and shielding model (based on the results described in Sec. 3.)

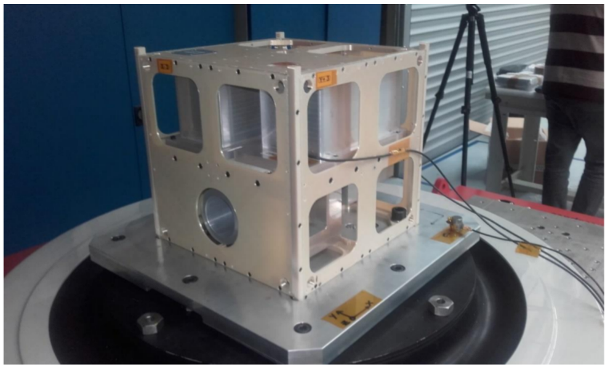

Figure 11: Picture of the prototype aluminum spacecraft on the vibration testing plate.

- a design for demise module (based on the results of 3.2).

All the modules are interfaced and linked, in a processing chain, through the openSF simulation framework properly configured and customised to adhere to the needs of the ReDSHIFT SW tool.

The core of the software is represented by the modules allowing the computation and characterization of the disposal trajectory for a given spacecraft at the end-of-life (e.g., see [16] for the LEO region). In the disposal module, given the initial orbit of the spacecraft and the spacecraft characteristics in terms of its cross area and mass, the optimal options for end-of-life disposal are given and compared. The end-of-life disposal can be attained by means of different options: via one or a sequence of impulsive manoeuvres, through the use of a solar/drag sail or through a hybrid sail and manoeuvre approach. This module is based on a study of the natural orbit evolution in the low to medium and geostationary regions that was performed to identify long-term stable orbits or resonance conditions to be used as graveyard or re-entry trajectories. The optimal manoeuvre to reach such re-entry or graveyard conditions is calculated. If the re-entry can be enhanced through a sail, different strategies for sail attitude control can be selected. The optimal disposal by this module is passed to the space environment module so that the effect of this disposal on the space debris environment is calculated. This is done based on precomputed long-term simulations of the whole space debris environment, under different scenarios, to be used for the computation of the collision risk for the spacecraft in the disposal phase. In the case the disposal trajectory is a re-entry one, the condition of the orbit at 120 km is used to verify the demisability of the spacecraft. This is done, by default, using some predetermined spacecraft configuration but the external user can also load a preferred configuration.

5. Legal aspects

The potential benefits of any proposed mitigation measure is often weakened by its limited practical application. A clear understanding of the complex legal framework of the space activities is therefore essential to try and enforce any innovative mitigation procedure. In the framework of the ReDSHIFT project a special effort is devoted to the study of the current international legal framework related to space debris in order to identify its deficiencies and propose possible advancements.

All international space debris mitigation instruments so far have a non-binding character and rely on voluntary adherence. Nevertheless, they provide with detailed practical guidelines (e.g., [11]). They may acquire a binding character provided that there is enough uniform practice which evolves to customary law. Moreover these guidelines also play a role by serving as a basis for national laws (such as the French and Austrian space law).

Two major problems can be immediately identified in the preliminary analysis of the existing national laws: there is no uniformity of national standards (e.g., different definitions of protected regions in LEO, MEO and GEO) and there appears different waivers with justification, for example for small satellites. In the analysis of an optimised legal and political framework able to better promote the application of improved guidelines it is important to explore how the new design technologies and rules foster specific branches of the economy. The aim of the legal/political and economical analysis within ReDSHIFT is also to push the space manufacturers towards innovative and possibly profitable directions. Therefore, next to legal mechanisms, also economic incentives could contribute to the 'attractiveness' of the adherence to mitigation standards if properly coupled with viable novel technical solutions. Following this strategy, a few examples of the proposed measures under study include:

- the possibility to exploit the newly identified re-entry "corridors" steering the space traffic towards these preferential routes for disposal, following the extensive cartography of the circumterrestrial phase space, as explained in Sec. 2.;

- the re-definition of the concept of residual lifetime implicit in the 25-year rule, towards a concept considering the actual interaction of a spacecraft with a given protected zone;

- the possibility to apply economic incentives to such promotion of deorbiting devices (similarly to what is sometimes seen on Earth in eco-friendly devices and transportation means).

Important indications, that should be conveyed as recommendations at the international level, are stemming also from the testing described in Sec 3.2. These include, as an example:

- For any uncontrolled re-entry a maximisation of the circularisation (possibly final apogee of the orbit below 500 km)i is desirable to limit the steepness of the re-entry, thus minimizing the landed mass and the resulting casualty risk.

- For very area augmentation devices, it is recommended for the system to break under force at altitudes of 150 km, in order that the trajectory does not steepen in the final stages of re-entry. This is recommended for all systems with area-to-mass ratios greater than 0.5 m^2/kg.

- Concerning the materials used in space hardware:
  - The use of titanium should be limited to very small objects.
  - Stainless steel is not recommended for reaction wheel flywheels. An alternative material is required.
  - 3D printed materials and standard materials are equally demisable.

- Improved demise is seen from early release of components, therefore the technologies which join structures and components are critical from a casualty risk perspective.

6. Conclusions

The H2020 ReDSHIFT project is approaching its completion [13]. A number of interesting goals which were briefly summarized in the above sections were achieved. In particular we can highlight:

- a complete mapping of the LEO to GEO space was performed and the cartography was exploited to devise "dynamical" disposal strategies for any orbital regime. All the maps are now publicly available on the project website (http://redshift-h2020.eu/)

- a small spacecraft "debris compliant" was designed and three prototypes were assembled exploiting the advantages offered by the additive manufacturing procedures. Several parts, including optimized debris shields, were designed and 3D printed.

- the 3D-printed items underwent hypervelocity and radiation tests.

- the materials and components of the spacecraft were tested for Design for Demise (D4D). Moreover the D4D tests included a novel test on a full mock-up of a CubeSat and on an engineering model of a reaction wheel.

- the possibility to exploit area augmentation devices (e.g., solar and drag sails) was studied both from the dynamical and the hardware point of view.

- a software tool (whose web version will be made public at the end of the project) encompassing all the above findings was produced. The software shall help the users to conceive a "debris compliant" space mission from the design to the disposal phase.

- the possible improvements to the international space regulations and standards, stemming from the projects findings, were analyzed.

As this fruitful collaboration approaches its nominal end, we believe that we have added a significant contribution to international studies on passive debris mititigation.

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