70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.

IAC-19,A6,6,4,x53705

THE H2020 REDSHIFT PROJECT: A SUCCESSFUL EUROPEAN EFFORT TOWARDS SPACE DEBRIS MITIGATION

A. Rossi[a]*, E.M. Alessi[a], G. Schettino[a], J. Beck[b], I. Holbrough[b], T. Schleutker[c], F. Letterio[d], Gonzalo Vicario de Miguel[d], J. Becedas Rodríguez[e], F. Dalla Vedova[f], H. Stokes[g], C. Colombo[h], I. Gkolias[h], F. Bernelli Zazzera[h], N. Miguel[h], S. Walker[i], F. Romei[i], K. Tsiganis[l], D. Skoulidou K.[l], E. Stoll[m], V. Schaus[m], R. Popova[n], Y. Kim[n], A. Francesconi[o], L. Olivieri[p], S. Gerardin[q]

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

* Corresponding Author

Abstract

The ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies) project was concluded on March 31, 2019. The 3-year project involved 13 European partners and was aimed at studying, implementing and testing novel solutions for space debris mitigation. The focus was on passive means to reduce the impact of Space Debris by prevention, mitigation and protection. The project was based on 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. The paper presents an overview of the main results of ReDSHIFT, in an effort to highlight the holistic approach of the project covering different aspects of the space debris mitigation field.

Keywords: Space debris mitigation; dynamical de-orbiting; additive manufacturing.

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. 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/)

[18].

The ReDSHIFT project was concluded on March 31, 2019. It was a 3-year project that displayed an impressive level of collaboration between 13 European partners, aimed at studying, implementing and testing novel solutions for space debris mitigation. The main results can be summarized as:

1. 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 (Sec. 2.).

2. 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 (Sec. 2.).

3. A prototype small spacecraft "debris compliant" was designed and assembled exploiting the advantages offered by the additive manufacturing procedures. After a first round of environmental tests the initial spacecraft design was revised and a new design, optimized for 3D printing, was obtained (Sec. 3.).

4. Several parts, including a solar/drag sail container, an in-orbit attach mechanism for sail module and new debris shields, were designed, 3D printed and tested. The sail mechanisms underwent deployment and mechanical tests, while the shields were tested with hypervelocity impacts (Sec. 3.2).

5. The materials and components of the spacecraft were tested for Design for Demise (D4D) (Sec. 3.2.1).

6. A software tool (whose web version is now publicly available on the project website: http://redshift-h2020.eu/) 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 (Sec. 4.).

7. A number of possible improvements to the international space regulations and standards, stemming from the projects findings, were analyzed and identified (Sec. 5.).

In the next sections a summary of all the above results will be presented with a specific focus on the most recent ones.

2. Phase space mapping and dynamical disposal scenarios

As also shown by the long term simulation of the environment performed within the project [19], 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, the most accurate dynamical mapping of the circumterrestrial space, from LEO to GEO, ever performed at this date was realized within ReDSHIFT. The results of the mapping effort were presented in a number of conferences and papers ([1] [2] [3] [9] [11] [17] [20] [21] [22]) and are therefore not repeated here in detail. Note that an electronic atlas with the maps was assembled and is now freely available from the project web site.

Here we briefly summarize the results of a set of long-term evolution simulations aimed at testing the effectiveness of the proposed dynamical disposal (the so-called "de-orbiting highways", i.e., the natural reentry corridors represented by the resonances) in limiting the accumulation of large objects in LEO after the end of the operational life. A detailed analysis of the simulations can be found in [4].

It is worth stressing that the dynamic disposal mapping was performed for all the circumterrestrial space, from LEO to MEO and GEO. Whereas these last simulations were limited to LEO, we briefly recall some of the results obtained for MEO and GEO:

- for the GNSS in the MEO region it was shown in the ReDSHIFT studies [23] [24] that stable graveyard orbits can be found a few hundred kilometers above the GNSS operational orbits. Moreover, exploiting the resonances, it is even possible to de-orbit the satellites towards the atmospheric reentry. It was also shown that, whereas the total disposal time is usually in excess of 25 years, the actual interaction between the disposed MEO satellites and the LEO region is well below the 25 years limit.

- For the GEO region, the analysis confirmed the possibility to permanently store the spacecraft in the super-GEO zone, according to the IADC formula. Moreover, in the case of the inclined

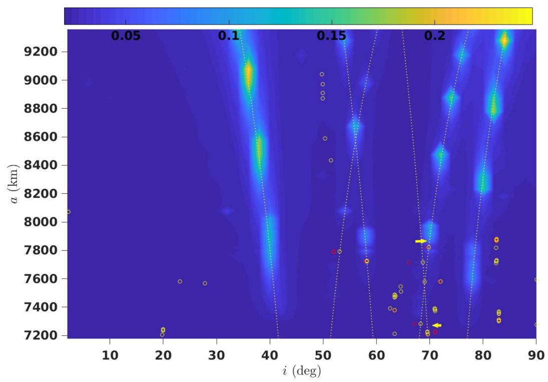

Figure 1: Sample of a map showing the location of the resonant corridors in LEO, in the semi-major axis vs. inclination space. The red and the yellow circles show the location of the original and of the displaced launch traffic respectively (see text for details). The color bar show the maximum change in eccentricity produced by a given resonance, as a function of the initial inclination and semi-major axis.

GEO orbits which are starting to be exploited, the possibility to de-orbit the satellite at the end-of-life thanks to the lunisolar perturbation and the related resonances was shown [9].

Most of the satellites with perigee below about 700 km are more or less "naturally" compliant with the 25-year rule. I.e., they can re-enter within the desired time span just exploiting the atmospheric drag. For higher orbits a significant ΔV might be required to comply with the existing guidelines. We note, in passing, that these upper LEO regions, above 1000 km of altitude, might become more popular in the coming years (e.g., with the forthcoming large constellations) in view of the relatively low spatial density of objects in those orbits. For these upper LEO satellites the possibility to exploit the "de-orbiting highways" offers a mean to significantly decrease the required ΔV , thus saving propellant and pushing towards a better compliance to the 25-year rule.

The main idea underlying the new set of simulations is to consider a standard 8-year repeating launch traffic scenario which is cycled all along the simulation time span. All the intact objects (including satellites, upper stages and MROs) are propagated for 200 years, disregarding in-orbit fragmentations. Different post mission disposal strategies are simulated considering the exploitation either of impulsive maneuvers, with different levels of applied ΔV, or the use of much smaller (in terms of ΔV) maneuvers coupled with the use of resonant corridors and area augmentation devices (bringing the final A/m to 1 m^2/kg).

The purpose of the simulations was to highlight the possible benefits of the "de-orbiting highways" in facilitating the disposal of the spacecraft at the end-of-life. Therefore, since as shown in Fig. 1 the resonances are located at specific inclinations it was decided to "artificially" move our launch traffic (both in inclination and in semi-major axis) towards the resonances. In other words, to enhance the signal coming out from the simulations, a displacing of the launch traffic was adopted. As an example, the small arrows and the different colors of the dots in Fig. 1 show the displacement of the launch traffic adopted in one of the simulated scenarios.

Without entering in the details described in [4], we show just one plot as an example of the obtained results. In Fig. 2 the comparison between six scenarios with and without the use of sails and corridors. In all the six cases the original launch traffic was initially moved, in semi-major axis, upward by 500 km (the purpose here is to avoid objects that can re-enter naturally under the effect of drag without the need of disposal maneuvers) and in inclination toward the closest resonant corridor. The blue and orange lines show the final number of objects when the disposal maneuver (which is a lowering of the orbit perigee) is done with a ΔV of 100 and 200 m/s, respectively. The other four lines relate to scenarios where a small ΔV (either 10 or 20 m/s) is used initially to move the objects inside a resonant corridor and where an area augmentation device is opened at the disposal epoch. The scenraios represented by the the yellow and purple lines differ from those represented by the green and cyan lines in the initial displacement of the launch traffic in terms of inclination. Whilst the very high orbits considered make the quite standard $\Delta V = 100$ m/s not effective to remove the spacecraft at the end-of-life, we note that the use of the area augmentation devices allows a significant reduction of the final number of objects. A comparable disposal efficiency can be attained by using only an impulsive strategy to lower the pericenter, without exploiting a sail, with a ΔV of 200 m/s, i.e., about one order of magnitude higher than the one needed by using the combination of the

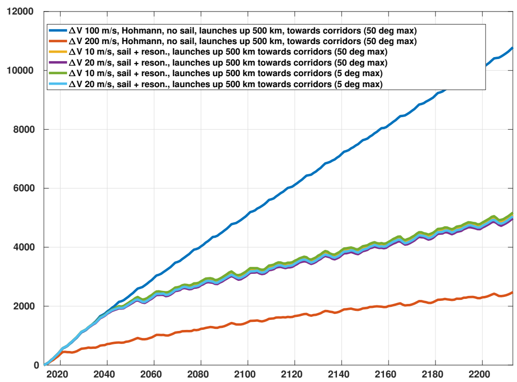

Figure 2: Number of objects as a function of time for the 6 different scenarios identified in the legend and described in the text.

corridors and the sail.

Whilst we are well aware that an hypothetical change in the launch traffic such as the one used in our simulation is not realistic, the results of Fig. 2 and of the other simulations show how the resonance corridors identified in the mapping, coupled with an area augmentation device, can be very effective in removing the majority of objects within 25 years from the end of the operational life, thus contributing to the stabilization of the space debris environment. Time is ripe to think about the disposal phase of the spacecraft at the early stage of the definition of the operational goals of a mission. A slight change in the initial orbital parameters (e.g., in terms of inclination or semi-major axis) might sometime guarantee the original mission purposes while paving the way to more effective and cheaper de-orbiting strategies. I.e., the possible changes in the mission design should be properly leveraged against the advantages encountered at the end of the operational life enabling a better compliance with the de-orbiting guidelines.

Finally, we remember that, on the basis of the dynamical findings briefly outlined above, a comprehensive software tool (see Sec 4.) allowing the definition of the best disposal strategy for a given spacecraft was produced.

3. Additive manufacturing

The experimental pillar of the ReDSHIFT project was mainly devoted to the design and production of a novel spacecraft by 3D printing. In fact, in an effort to make novel technological solutions easier and more attractive to produce and to implement into future design, thus enhancing the debris-oriented vision of spacecraft manufacturing, ReDSHIFT explored the possibility to use the now blossoming additive manufacturing technology, to actually realize a model spacecraft and some specific parts related to the debris mitigation issues, such as, e.g., the shielding, a sail canister, the sail hatches and joints, etc. [12] [26]. Beyond the model spacecraft, over 340 smaller samples were produced with the 3D printers and have been used to test the capabilities of the additive manufacturing.

The selected prototype spacecraft was an 8U CubeSat (200 x 200 x 200 mm) for an Earth Observation multi-spectral mission. The general procedure followed within the project was the following. First a "traditional" design of the cubesat was produced (see [18]) and the first prototypes were produced. Three similar spacecraft were assembled: one in aluminium with traditional CNC milled panels, one with 3D printed aluminium panels and one in a plastic material called ULTEM^{TM} [5]. Then, the three spacecraft underwent a thorough environmental testing campaign (e.g., thermal vacuum, vibration) [6]. Finally, on the basis on the test results the design was updated and a more advanced exploitation of the additive manufacturing techniques was explored and applied [26]. The Figs. 4 to 7 show some details of the final 3D printed spacecraft. Note that, as can be hinted looking at Fig. 4 the walls of the spacecraft were produced with an internal lattice structure which proved, at the same time, extremely light and resistant [26]. Also the final prototype underwent a full campaign of environmental test.

Not only did all these components pass the environmental test campaigns but they demonstrated an overall mass reduction of just under 30 %.

The application of 3D printing to medium and large satellite primary structures through monolithic cores was a completely original area of research performed within ReDSHIFT. Although for these initial studies the 3D printed cores generally result in a structural mass increase the structural mass ratio can be significantly improved. The geometrical design freedom enabled by 3D printing allows a greater optimisation of many structural parameters such as insert failure loads, compression loads and bending loads which over future test iterations will result in mass reductions. A good example of this is the core

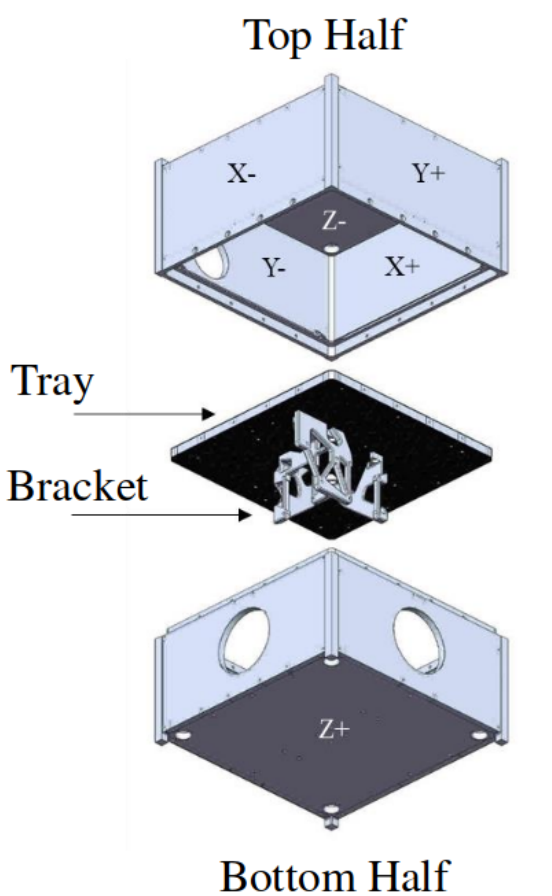

Figure 3: New design of the ReDSHIFT 3D printed proptotype.

of the 3D printed tray (Fig. 6) for the second iteration of the small spacecraft structure. By printing the core, the multiple multi-axis inserts could be accommodated into a small honeycomb sandwich structure that significantly outperformed the previous solution with an 80 % reduction in mass. The 3D printing techniques were applied to spacecraft shielding. Although relatively simple geometries were manufactured and tested (see Sec. 3.1 and Fig. 8), the geometrical design freedom offered by this manufacturing method resulted in samples that demonstrated excellent shielding properties. The application of 3D printing to improve the demisability of spacecraft structures and components was assessed too. Due to the limited knowledge and general understanding of spacecraft re-entry breakups, only a small number of 3D printed samples were

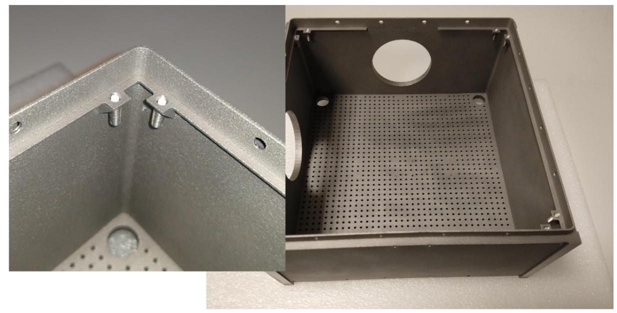

Figure 4: Details of the internal structure of the ReDSHIFT 3D printed proptotype.

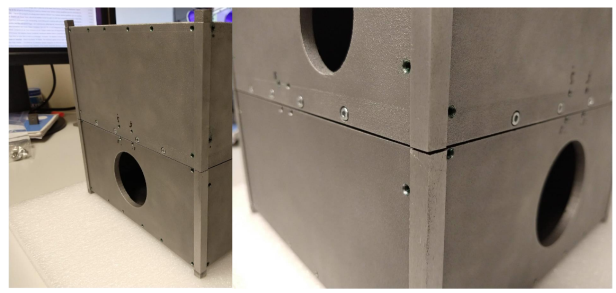

Figure 5: External view of the ReDSHIFT 3D printed proptotype.

tested. However, it has been seen that the use of monolithic cores with inserts demonstrates a more predictable failure of the insert when compared to standard inserts which require a significant amount of potting compound. This compound has a high specific heat capacity and can delay the failure of the insert. Therefore, monolithic cores have the potential to enable the satellite joint lines to fail at an earlier stage of the re-entry, speeding up the access of the heat flux to the inner components, and as a result improving the demisability of the satellite. Overall the application areas of metal 3D printing in satellite design, explored through experimental testing within the ReDSHIFT project, have all demonstrated the future potential of this technology. Further research needs to be performed to raise the readiness level of this technology but the work performed within ReDSHIFT has created an excellent foundation for this next step.

3.1 Shielding

The purpose of the shielding activity within ReDSHIFT was to define and assess new shielding concepts for protecting unmanned spacecraft against

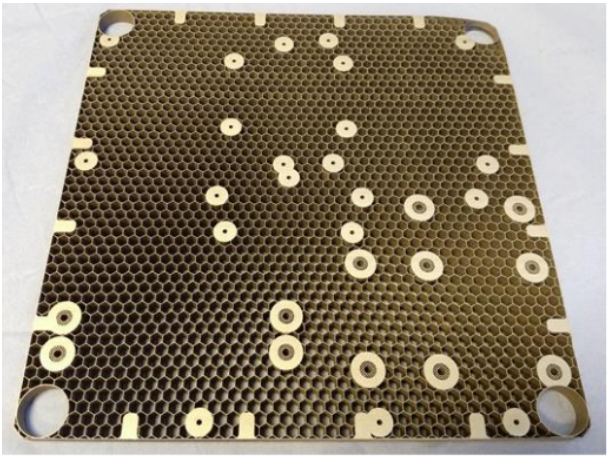

Figure 6: The honeycomb internal structure of the tray.

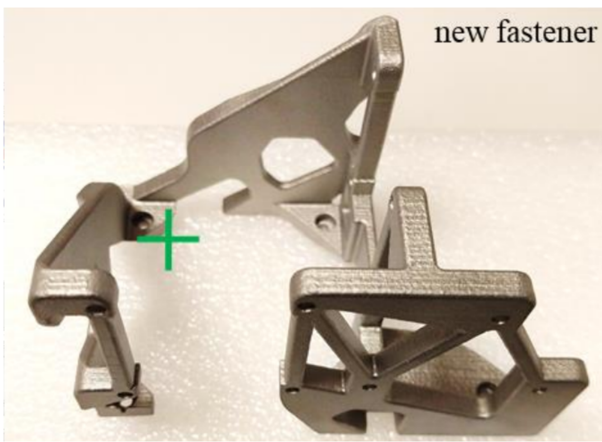

Figure 7: The new 3D printed reduced weight fastener.

non-catastrophic micrometeoroid and orbital debris impacts. Since 3D-printing was used to manufacture the shields, the work focused on the definition of promising shielding solutions which might be difficult to realise using traditional manufacturing techniques.

The overall process of definition and production of debris shields within ReDSHIFT was the following:

1. Several promising debris shielding concepts were identified, including two baseline concepts, i.e. a multi-shock panel and a single corrugated panel, and several advanced concepts, such as a double corrugated panel and a hybrid panel. All of these designs were the subject of a comprehensive set of tests, including hypervelocity impacts to characterise their performance.

2. A preliminary impact risk analysis was performed using the SHIELD3 model [25] to perform an approximate evaluation of the shielding performance of the two baseline shields, i.e. the multi-shock panel and the single corrugated panel. The results of the assessment were expressed in several ways. Firstly, the ballistic limits of the shields were estimated. Secondly, the probability of penetration of a box-shaped spacecraft was calculated when the shields are applied to each surface. Finally, the optimum design solution for each shield was identified.

3. Based on the results of the preliminary impact risk analysis, the design parameters of the baseline shields were defined for the first phase of the investigation, which focused on 3D-printing the shields and subjecting them to a variety of tests for evaluation purposes (Sec. 3.2).

4. The design parameters of advanced shield concepts were then defined using knowledge gained from testing of the baseline shields. The advanced concepts were then 3D- printed (see Fig. 8) and tested in the second phase of the investigation (Sec. 3.).

5. A final impact risk analysis was performed using the SHIELD3 model to quantify the performance of the advanced shield concepts. To do this, damage equations derived from impact tests in the second phase of the investigation were implemented in SHIELD3. The results of the analysis were also used as an input to the ReDSHIFT Software Shielding Module, described in Sec. 4..

From the results of the impact test programme and impact risk analyses it was concluded that:

- It is possible to produce complex shield configurations with 3D-printing, whereas the same shields might be difficult to manufacture using traditional methods.

- The use of 3D-printing to manufacture a shield, as compared to standard techniques, does not appear to compromise the shield's effectiveness.

- The performance of a shield panel is driven mainly by the panel's core configuration, its

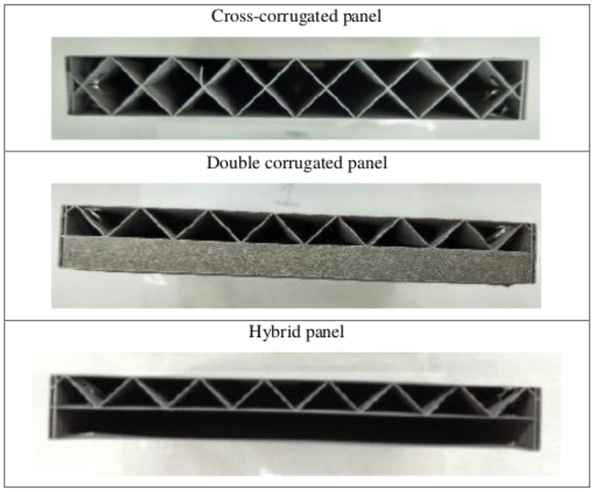

Figure 8: Examples of a 3D-printed Cross Corrugated Panel (top), Double Corrugated Panel (middle) and Hybrid Panel (bottom)

areal density and its stand-off distance to a rear wall.

- A panel comprising a corrugated bumper layer in its core appears to offer slightly improved impact protection compared to an equivalent panel that uses flat bumpers.
- A hybrid shield panel provides a substantial level of impact protection compared to an equivalent standard honeycomb sandwich panel design.
- The damage caused by a penetrative debris cloud inside a spacecraft can be modelled in impact risk analysis codes quickly and accurately using a newly-derived equation which calculates a so-called "perforation spread angle".

Each of these conclusions represents a significant advance in the field of debris shielding research. Therefore, one might expect that 3D-printed shield panels will become commonplace in the construction of spacecraft in the not-too-distant future. In fact this is already starting to happen for very small satellites (e.g. cubesats).

3.2 Testing

A massive test campaign was performed on all the samples and prototypes produced with the 3D printing techniques and on other samples commonly used in the space missions in the case of the Design for Demise (D4D) testing. A short description of every testing campaign follows.

3.2.1 Design for Demise tests

The main objective of the D4D testing campaign was to provide basic phenomenological data on the demise of particular spacecraft materials and structures such as:

- Aluminium
- CFRP and Sandwich materials
- Representative spacecraft components

A significant number of innovative tests were performed with the aim of identifying the key gaps in our current knowledge and understanding of the D4D processes. In particular, the tests were aimed at understanding the following issues:

- Shear testing of aluminium
- Understanding what happens to facesheets when removed
- Test complete complex structures such as reaction wheels and CubeSats.

The tests were performed in the DLR L2K facility. There were many "Firsts" in the ReDSHIFT Demise Test Campaign. The results of the D4D tests are described in detail in the [7]. Here we briefly recall some of the specific tests along with some of the main conclusions:

- First tests of aluminium thin structures: Top hat, Plate, CubeSat Structure, Reaction Wheel Housing. The results point out:
  - A significant strength of oxide is observed, such that some force is required for removal;
  - There is some delay in the separation/fragmentation after the melt point is reached.
- First tests of complete satellite (CubeSat). The results point out:
  - The satellite structure melts but the steel rods for mounting can still the support structure after the strong heating;

  - The GFRP electronics cards are more robust than expected.

- First tests of real spacecraft equipment. An engineering model a real reaction wheel was tested. The results point out that:
  - The observed demise process is very different from models;
  - Many small parts are produced;
  - The heating distribution is evident and the curvature is clearly important.

3.2.2 Hypervelocity impacts tests

The hypervelocity impact tests campaign was performed with the two-stage light gas gun at the CISAS hypervelocity impact facility and by means of ad-hoc computer simulations [13]. The main objectives were to exploit the opportunities given by additive manufacturing in designing and printing a small spacecraft with complex geometry of the panel core, with limited/no junctions.

The tested shields showed enhanced shielding capability with very fine debris fragmentation and marginal damage to spacecraft internal components. In terms of satellite components protection, all shield configurations outperform honeycomb sandwich panels of equivalent thickness and surface density. This is mainly due to the panels geometry, while the effect of the manufacturing process is less relevant. A debris cloud model for the above panels have been implemented as input for the Space Debris Shielding Module of the ReDSHIFT software (see Sec. 4.). Moreover, the effect of structural fault lines in satellite fragmentation has been studied with numerical simulations, using the new semi-empirical Collision Simulation Tool developed, by CISAS-UniPD, in the frame of the ESA contract "Numerical Simulations for Spacecraft Catastrophic Disruption Analysis" [14]. The goal is to assess the possibility of controlling satellite fragmentation through the use of pre-determined fault lines in the spacecraft structure. Fault lines effects are dependent from the collision configuration (impact point and impactor/target size ratio), with observed disadvantages in central impacts (reduced impact energy dissipation) but benefits in glancing impacts (limited fracture propagation along structure). Given the variety of possible collision scenarios and the expected majority of glancing impacts, fault lines could be a good candidate for reducing the severity of large collision events involving entire spacecraft and/or rocket bodies.

3.2.3 Radiation tests

The purpose of the radiations tests was to evaluate the shielding potential of different aluminium structures with respect to the space radiation environment, through a set of simulations and experiments. High energy protons were chosen for this assessment because they are the most abundant particles in space and they are extremely relevant for the Low Earth Orbit (LEO) environment and are the most penetrating particles, having the longest range for charged particles at a given energy, due to the low rate of ionization. Moreover, protons can also generate secondary effects through nuclear reactions, which are less frequent with heavier particles. Two radiation sensitive devices were used to assess the modifications induced in the proton beam by five aluminium shields:

1. RADFETs (radiation monitors)
2. NAND Flash memories (commercial devices that can suffer from radiation effects)

Radiation-matter interaction Monte Carlo simulations were performed to evaluate proton transport through the shields and the layers above the active regions of the monitoring devices. Then, based on simulation results, an ad-hoc irradiation campaign was performed with 24.76 MeV protons. The results showed that, for both types of radiation monitoring devices, the geometry of the aluminium shield has little impact on the shielding effectiveness. The various shields behave as aluminium layers with an equivalent thickness given by the sum of the thicknesses crossed by the proton beam in the actual shield.

3.2.4 Mechanical and Thermal Vacuum (TVAC) testing

The components and the satellite prototypes produced with the 3D printing underwent a thorough testing campaign to verify their suitability for a launch with the most common rockets and their capability to survive in the harsh thermal vacuum environment in space. Both the aluminium and the ULTEM-made satellites were tested. The first tests were performed on the "traditional" structure and then used to retrofit on the innovative design of the spacecraft, optimized for the 3D printing processes. In essence, it can be stated that the ULTEM$^{(TM)}$ structure was proven to damp the high frequency vibration which is beneficial for the on-board electronics [6]. While the 3D printed aluminium structure provided a similar behaviour compared to the CNC one, so the implementation of 3DP geometries became less risky. The TVAC test of the ULTEM^{TM} structure proved that the thermoplastic structure is viable in space and that the thermal insulation inherent to the material could be useful to reduce the power required for thermal control via heaters. Both sails-related mechanisms [12] successfully passed the entire tests with a reduction in mass due to 3D printing. Finally, the modification in the aluminium 3D printed structure provided outstanding results. The frequency of this mode was doubled in the lateral axes with half the mass while the frequency in the longitudinal one did not change. In addition, the ultimate load was highly increased due to the removal of several screws. Moreover, no dangerous local mode was detected in the star trackers so the new bracket can be considered a success that contributed to reduce the mass while maintaining the mechanical performance. Therefore, it was proven that the use of 3D printing with exclusive geometries like lattice patterns, topological optimization and integration at manufacturing level are indeed viable options for space primary structures with a positive significant impact on the performance.

4. Software

Within ReDSHIFT, a large software suite was produced both as a a standalone package distributed inside the consortium members and as a web-based tool freely accessible with a registration on the project portal at https://redshift-webtool.elecnor-deimos.com/webtool/login.html. The 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 are five interconnected modules:

- a disposal module (based on the results described in Sec. 2.) described in detail in [21] and [10].
- a sail module (based on the results described in Sec. 2.) computing the required sail to dispose without impulsive manoeuvres adopting either a passive sail approach (i.e., with fixed attitude) or a modulating sail approach (i.e., with a variable attitude) if the passive approach is not feasible due to technological limits (e.g., sail size) [8].
- an environment projection module, allowing the computation of the flux and collision probability over a target orbit. The flux of particles of different sizes can be considered: 1 mm, 10 mm and 10 cm. In particular, the particles around 1 mm are relevant for debris shielding modules. Note that the flux results are obtained by extrapolation from the long-term evolution of the space debris environment (from LEO to GEO) with 7 scenarios based on different debris mitigation assumptions.
- a design and shielding model (based on the results described in Sec. 3.) using the data from environment projection module to characterize the impacts in terms of collision probability and impact velocity and particle size.
- a design for demise module (based on the results of 3.2.1) generating an initial assessment of the fragmentation and demise of a S/C re-entering the Earth's atmosphere with the possibility for the user to input a catalogue of critical components.

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.

5. Legal aspects

The complexity of space debris concerning the usability of outer space in a long-term perspective does not only require adequate regulation. It demands a holistic approach that provides a pragmatic trade-off between the restrictions needed and their benefits. For this purpose, the relevance for the implementation of legal measures for space debris of all the technical findings obtained within ReDSHIFT were explored.

A global strategy - both on the technical and on the legal level, from the planning of the mission and spacecraft design, up to end-of-life - is needed.

Legal efforts to minimize space debris should not be concentrated only on compliance and enforcement of existing guidelines. These must be adapted, extended and supported by (new) legal and economic measures.

By premising the legal analysis on technical findings, possibilities to re-formulate the existing regulations are proposed and discussed in detail in [16]. The proposals include:

- A revised interpretation of the 25 year-rule for MEO, aiming, e.g., at the deorbiting of GNSS satellites at end-of-life [15]. In the dynamical studies it was shown how deorbiting even from the MEO region is possible, with a moderate ΔV. Whilst these deorbiting trajectories require more than 25 years to actually bring the spacecraft back into the atmosphere, it was shown how the actual interaction between the spacecraft and the LEO protected region is minimal and never exceeds 25 years (actually it is significantly shorter). Therefore a provision stating that only the time spent within the protected region (as opposed to the total residual lifetime) could be adopted.

- An add-on to GEO disposal rules, accounting for the growing exploitation of inclined GEO orbits, for natural end-of-life re-entry. As it was shown in the dynamical studies, the inclined GEO orbits lie in a very unstable region of the phase space. Hence this instability can be exploited to reach a fast reentry which is, for these specific spacecraft, actually much cheaper (in terms of $DeltaV$) than a maneuver aiming at reaching a stable super-GEO graveyard. The same caveat about the interaction with the protected regions as in the above bullet apply here.

- Recommendations to limit the orbital lifetime in LEO and MEO by exploiting orbital resonances. As it was described in Sec. 2., the use of the resonant corridors can help in enhancing the effectiveness of the disposal maneuvers and the adherence to the mitigation practices.

- The use of augmentation devices for deorbiting also from orbits higher than LEO.

- Recommendations for demisable materials. The new tests performed within ReDSHIFT showed how, even for small spacecraft (CubeSats) or for devices of widespread use (e.g., reaction wheels), a significant share of the material can survive the reentry conditions. A careful choice of the materials should therefore be done taking into account the full demisability of the spacecraft, at the design stage. This can become even more important if, as suggested above, the atmospheric reentry becomes an option even for MEO and GEO spacecraft which historically were not designed with this fiery destiny in mind.

- Economic incentives to promote Active Debris Removal (ADR). While it is true that a market for ADR is blossoming, an international coordinated and financed effort could be devised to promote a global action to remove the most dangerous abandoned spacecraft in the critical regions of LEO. Examples of this good practice can be found in other terrestrial and maritime operations.

In essence, the ReDSHIFT paradigm and the proposed guidelines amendments can be viewed as a will to consider space debris compliant space missions from the early design stage both in terms of spacecraft structures and in terms of orbital dynamics.

6. Conclusions

The H2020 ReDSHIFT project was concluded at the beginning of 2019. 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 environmental, 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 in publicly available at the project website) 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.

We believe that the ReDSHIFT project represented a very successful contribution in the field of passive debris mititigation and a fruitful example of the power of the H2020 European collaborative efforts.

Acknowledgments
This work is funded through the European Commission Horizon 2020, Framework Programme for Research and Innovation (2014-2020), under the ReDSHIFT project (grant agreement n. 687500).

References

[1] Alessi E.M., G. Schettino, A. Rossi,G. B. Valsecchi, Solar radiation pressure resonances in Low Earth Orbits, *Mont. Not. R. Astron. Soc.*, *473*, 2407-2414, doi:10.1093/mnras/stx2507 (2018).

[2] Alessi E.M., G. Schettino, A. Rossi and G.B. Valsecchi, LEO mapping for passive dynamical disposal, in *Proc. 7th European Conference of Space Debris, Darmstadt, Germany, 2017, 18-21 April, SDC7-508.*

[3] Alessi E.M., G. Schettino, A. Rossi and G.B. Valsecchi, Natural Highways for End-of-Life Solutions in the LEO Region, *Cel. Mec. Dyn. Astron.*, 130:34, https://doi.org/10.1007/s10569-018-9822-z (2018).

[4] Alessi E.M., A. Rossi, V. Schaus, G. Schettino, and G.B. Valsecchi, How an aware usage of the long-term dynamics can improve the long-term situation in the LEO region, Paper IAC-19,A6,2,5,x53774, *70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.*

[5] Becedas J. and Caparrós A., Additive Manufacturing Applied to the Design of Small Satellite Structure for Space Debris Reduction, in *Applications of Design for Manufacturing and Assembly*, http://dx.doi.org/10.5772/intechopen.78762, IntechOpen, 2018.

[6] Becedas J., A. Caparrós, A. RamÃrez, P. Morillo, E. Sarachaga, A. MartÃn-Moreno, Advanced Space Flight Mechanical Qualification Test of a 3D-Printed Satellite Structure Produced in Polyetherimide ULTEM^{TM} in *Advanced Engineering Testing*, http://dx.doi.org/10.5772/intechopen.79852, IntechOpen, 2018.

[7] Beck J., Improved representation of destructive spacecraft re-entry from analysis of high enthalpy wind tunnel tests of spacecraft structures and equipment Paper IAC-18,A6,2,5,x43971, *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.*

[8] Colombo C. and T. de Bras de Fe, Assessment of Passive and Active Solar Sailing Strategies for End-of-Life Re-entry, paper IAC-16-A6.4.4, *Proceedings of the* 67th *International Astronautical Congress*, 2016.

[9] Colombo C. and Gkolias I., Analysis of orbit stability in the geosynchronous region for end-of-life disposal, in *Proceedings of the 7th European Conference on Space Debris*, Darmstadt, Germany, 2017.

[10] Colombo C., G.V. de Miguel D. Skoulidou, N. Miguel, E.M. Alessi, I. Gkolias, F. Letterio, G. Schettino, K. Tsiganis, A. Rossi, ReDSHIFT disposal module for the design of end-of-life disposal trajectories for LEO to GEO missions, Paper IAC-19,A6,6,4,x53705, *70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.*

[11] Gkolias I. and Colombo C., End-of-life disposal of geosynchronous satellites, paper IAC-17-A6.4.3, *Proceedings of the* 68th *International Astronautical Congress*, Adelaide, 25-29 September 2017.

[12] Dalla Vedova F., Morin P., Roux T., Brombin R., Piccinini A. and Ramsden N., Interfacing Sail Modules for Use with "Space Tugs", *Aerospace*, 5, 48, doi:10.3390/aerospace5020048 (2018).

[13] Olivieri L., C. Giacomuzzo, A. Francesconi, S. Geradin, M. Bagatin, A. Paccagnella, A. Finozzi, H. Stokes, F. Romei, S. Walker, A. Rossi, Experimental characterization of multi-layer 3D-printed shields for microsatellites, Paper IAC-18,A6,3,7, *69th International Astronautical Congress (IAC)*, Bremen, Germany, 1-5 October 2018.

[14] Francesconi A., C. Giacomuzzo, L. Olivieri, G. Sarego, M. Duzzi, F. Feltrin, A. Valmorbida, K.D. Bunte, M. Deshmukh, E. Farahvashi, J.Pervez, M. Zaake, T. Cardone, D. de Wilde, CST: A new semi-empirical tool for simulating spacecraft collisions in orbit, *Acta Astronautica* 160 (2019), pp.195-205

[15] IADC (Inter-Agency Space Debris Coordination Committee), IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, 2007.

[16] Popova R., A. Rossi, Y. Kim, C. Colombo, E.M. ALessi, I. Gkolias, J. Beck, V. Schaus, K. Tsiganis, The path to establishing an effective framework for space debris remediation on the basis of mitigation: legal proposals resulting from the technical results of the ReDSHIFT project, Paper IAC-19,E7,7,4,x53789, *70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.*

[17] Rosengren A., Skoulidou D.K., Tsiganis K., and Voyatzis G., Dynamical cartography of Earth satellite orbits, *Adv. Spa. Res.*, 63 (2019)

[18] Rossi A. et al., ReDSHIFT: A Global Approach to Space Debris Mitigation, *Aerospace*, 5, 64, doi:10.3390/aerospace5020064 (2018).

[19] Schaus V., J. Radtke, E. Stoll, A. Rossi, C. Colombo , S. Tonetti, I. Holbrough, Results of reference long-term simulations focussing on passive means to reduce the impact of space debris, in *Proceedings of the 7th European Conference on Space Debris*, Darmstadt, Germany, 2017.

[20] Schaus V., E.M. Alessi, Schettino G., Rossi A., Stoll E., On the practical exploitation of perturbative effects in low Earth orbit for space debris mitigation, *Adv. Spa. Res.*, 63 (2019).

[21] Schettino G., Alessi E.M., Rossi A., Valsecchi G.B., Exploiting dynamical perturbations for the end-of-life disposal of spacecraft in LEO, *Astronomy and Computing*, 27 (2019).

[22] Schettino G., Alessi E.M., Rossi A., Valsecchi G.B., A frequency portrait of Low Earth Orbits, *Cel. Mec. Dyn. Astron.* 131:35 (2019).

[23] Skoulidou, D.K., Rosengren, A.J., Tsiganis, K., Voyatzis, G., 2017. Cartographic study of the MEO phase space, in *Proceedings of the 7th European Conference on Space Debris*, Darmstadt, Germany, 2017.

[24] Skoulidou D.K., A.J. Rosengren, K. Tsiganis, G. Voyatzis, Dynamical Lifetime Survey of Geostationary Transfer Orbits, *Cel. Mec. Dyn. Astron.*, 130:77 (2018).

[25] Stokes H., Space debris risk assessment of spacecraft protected by 3D printed panels, Paper IAC-18,A6,IP,19,x45205, *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.*

[26] S.J.I. Walker, F. Romei, J. Becedas Rodríguez, F. Dalla Vedova, J. Beck, I. Holbrough, A. Francesconi, L. Olivieri, A. Caparrós, G.R. Flores, P. Morillo, H. Stokes, A. Rossi, C. Colombo, An Overview of the Application of 3D Printed Spacecraft Structures within the ReDSHIFT Project, Paper IAC-19,C2,5,2,x52963, *70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.*