THE H2020 PROJECT REDSHIFT: OVERVIEW, FIRST RESULTS AND PERSPECTIVES

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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. In ReDSHIFT these goals will be achieved through a holistic approach that considers, from the outset, opposing and challenging constraints for the space environment preservation, the spacecraft survivability in the harsh space environment and the safety of humans on ground. 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. The paper presents a quick overview of the first ReDSHIFT results in an effort to highlight the holistic approach of the project covering different aspects of the space debris mitigation field. Detailed reports on the results of the single Work Packages can be found in other papers in this same volume.

Keywords: ReDSHIFT; passive mitigation measures; 3D printing; design for demise.

1. INTRODUCTION

The ReDSHIFT project is structured in three main sections, striving to enhance possible synergies helping the space debris mitigation. First there is a more theoretical part, which is described in detail in Secs. 2 and 3. Here, initially, the currently adopted mitigation measures are scrutinized and evaluated, looking for the main positive and weak points by means of a literature survey and of several long term evolution projections. The aim of this study is to address and steer the efforts of the other Work Packages of the proper to the most promising areas of the mitigation procedures. At the same time, the long term simulations will serve as a reference against which to evaluate the effectiveness of the solutions analyzed and studied in the other Work Packages of the project. In the same context, the mitigation measures (both the present and the newly proposed ones) will be scrutinized in terms of the underlying legal and normative issues, in order to maximize their applicability and effectiveness.

At the same time, a detailed study of the dynamics of the circumterrestrial space is performed (Sec.3), by mapping the phase space from the LEO (Low Earth Orbit) to the GEO (Gestationary Orbit) region, studying the stability and instability areas. The idea here is to exploit the former as, possibly interim solutions, graveyard zones and the latter as "highways" to de-orbit easing and, hence, enhancing the compliance to the proposed de-orbiting mitigation measures. The mapping shall be exploited by proposing affordable maneuvers to move the spacecraft at the end-of-life towards the most favorable regions of the phase space. This includes also the study of the possibility to use passive means to de-orbit, such as area augmentation devices (solar and drag sails).

The experimental part of the projects (Sec.4) is looking at how the novel opportunities offered by the additive manufacturing (3D printing) can help in producing spacecraft

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parts that can help in minimizing the production of debris. Following the recommendations stemming from the theoretical studies mentioned above, the proposed area augmentation devices will be specifically studied and tested. Particular care will be devoted also to the demisability of the studied components upon re-entry into the atmosphere.

Finally all the findings will be assembled in a comprehensive software package, that will be made freely available (in a slightly reduced web version) on the web site of the project (http://redshift-h2020.eu/).

ReDSHIFT is now well within its second year of activities. The results achieved so far are discussed in detail in other papers in this same volume. They will be briefly summarized here to draw a global picture of the ReDSHIFT project.

2. ANALYSIS OF THE CURRENT MITIGATION MEASURES AND LONG TERM SIMULATIONS

A critical analysis of the strength and weaknesses of the currently adopted mitigation measures was performed. For more details on this subject see the paper by Schaus *et al.* in this volume.

To assess and quantify their effectiveness and to set a reference for further analysis in the second phase of the project, specific long term debris environment simulations were performed with the evolutionary models LUCA [5] and SDM [8].

Several different scenarios were simulated, distributing them between LUCA and SDM. The whole LEO to GEO environment was taken into account. A Reference scenario, mimicking the current operational and mitigation procedures, was first agreed, against which to compare the results of the modified scenarios. The modified scenarios were devised in such a way to possibly clearly highlight the effect of a single well defined parameter on the long term evolution of the population. Hence, these scenarios included:

- the effect of a widespread use of collision avoidance, for the active satellites;
- the effect of a increased compliance with the currently proposed mitigation measures (such as the 25-year rule) from the reference value of 60 % to 90 %;
- the effect of a reduced residual lifetime after disposal (from 25 to 10 years);
- the effect of active debris removal (one case with 2 objects per year and one with 5 objects per year);
- the effect of the launch of a mega-constellation of satellites in LEO (2 different cases);
- the influence, in the computation of the collision probabilities and of the collision consequences, of considering that a significant portion of the satellites have appendages (e.g., antennas, panels, etc).

Special care was taken into the analysis of the re-entry statistics and conditions of the disposed spacecraft, to be used as input for the design for demise analysis to be performed in the experimental part of the project.

For sake of conciseness we are not showing here the plots of the simulation results. The interested reader can see the paper by Schaus *et al.* in this volume. We limit ourselves to a short summary of the main results:

- as known confirmed by a number of previous studies (e.g., within the IADC Working Group 2 joint simulation efforts), the LEO environment appears "unstable", with the population growing notwithstanding the currently adopted mitigation measures.
- More aggressive mitigation measures can slow down the growth pace, but not stop or revert it.
- The use of super-LEO storage zone should be "handled with care", to avoid accumulation of uncontrolled objects possible leading to unavoidable collisions on the long term.
- The increased collision avoidance success rate, the improved mitigation compliance and the effect of the appendages all show a positive effect, reducing the mean number of collision fragments recorded in the simulation. Nonetheless the effect are relatively small with respect to the 1σ statistical significance of the Reference scenario.
- The simulation of appendages and the related collision dynamics should be taken properly into account to avoid over-estimation of the collisional activity in LEO.
- The planned mega constellations might represent a big issue in the future of the LEO environment, hence a careful look should be kept on them and on the way their operations are handled.
- In none of the simulated scenarios, with the notable exception of the very demanding Active Debris Removal of 5 objects per year, the adopted mitigation measures are enough to reverse or stop the growth of the population.
- In the GEO region an almost linear growth of objects is observed with, superimposed, as increase of fragments due to about one catastrophic collision (on average) happening between disposed objects cumulated in the GEO graveyard zone. Once again, there is the warning that these storage zone must be handled with extreme care to avoid the creation of "reservoirs" of collisional target in a not too distant future. This is particularly true for the GEO region where, e.g., active debris removal missions appear at the moment beyond reach.

3. DYNAMICAL MAPPING

One of the main purposes of this task is to evaluate the possibility of defining innovative strategies for designing disposal trajectories by examining the existence of natural "dynamical de-orbiting highways" in phase-space that could enhance orbit decay, by leading to high-enough eccentricities, within a realistic time-scale. In the absence of such solutions, a graveyard solution must be considered. A thorough exploration of the whole phase space enabled us to show, apart from the predominant role of atmospheric drag at low altitudes, the dominant role of SRP-related resonances at high LEOs, in conjunction with luni-solar resonances. Its effect for eccentric orbits on long time-scales was evaluated for the first time. We have shown that, especially around some well-defined (by virtue of the dynamics) inclination values, re-entry can be achieved on realistic time-scales. Although re-entry times can typically exceed the IADC 25-year rule, a strategy could be defined such that, allowing for a small Δv budget, an orbit can be forced to follow an eccentric re-entry solution. The possibility to exploit active and passive propulsion systems (such as solar and drag sails) able to steer the spacecraft toward the right "highway entrance" is currently studied. The highways are denoted on global dynamical maps, that will be finally collected in an "atlas" to be made publicly available through the project website.

By analyzing the distribution of the space objects in the orbital element space, a grid of initial conditions for an extensive numerical study was defined by first dividing the task into three regions: LEO, MEO and GEO (e.g., see Table 1 for the LEO grid and the papers by Alessi *et al.*, Skoulidou *et al.* and Colombo *et al.* in this volume for further details.

As an example, the dynamical mapping of the highly populated LEO region by studying the dynamics of sample objects over a 120 years time span. The propagation has been obtained by means of the long-term orbit predictor FOP [1, 8], which integrates singly-averaged equations of motion.The numerical integrator is a multi-step, variable step-size and order one. The dynamical model includes the gravitational contributions due to Earth (5×5 geopotential), Moon and Sun (as third-body perturbations), the solar radiation pressure (SRP) and the atmospheric drag (adapted Jacchia-Roberts density model, assuming a drag coefficient $C_D = 2.1$). The initial conditions in semi-major axis a, eccentricity e, inclination i, longitude of the ascending node Ω and argument of pericenter ω are sampled over a fine grid, shown in Table 1. We considered two initial epochs, 22 December 2018 and 21 June 2020, and two different values for the area-to-mass ratio, an average value $A/m = 0.012\,\mathrm{m}^2$/kg for intact bodies and an augmented value $A/m = 1\,\mathrm{m}^2$/kg, to account for a sail which can be achieved with present technology.

For each set of initial conditions, we analyzed the results by means of color maps representing the lifetime or the maximum eccentricity as a function of the initial

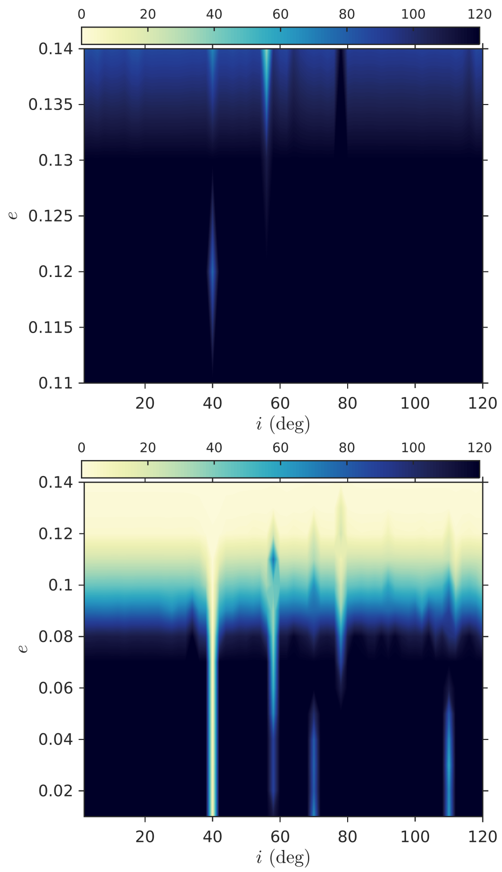


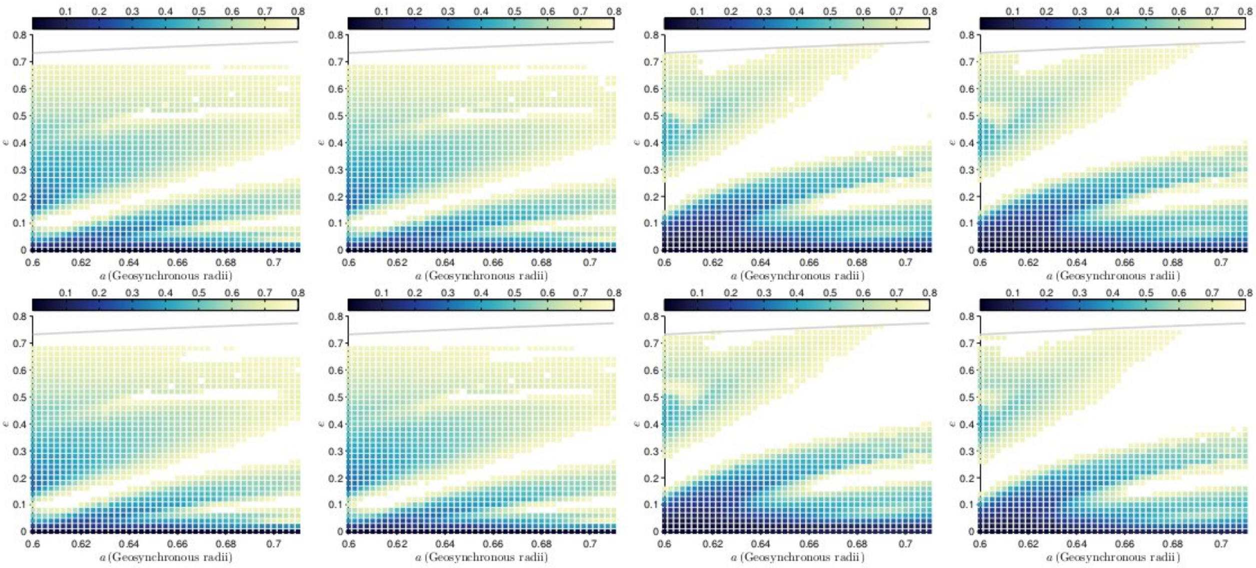
Figure 1. Lifetime, computed over 120 years, as a function on initial inclination and eccentricity, for initial $a = R_E + 1520\,km$, $\Omega = 0°$, $\omega = 180°$, epoch 2020 and $C_R A/m = 0.024$ m^2/kg (top) and $C_R A/m = 1\,m^2/kg$ (bottom) respectively.

inclination and eccentricity. An example for the case $a = R_E + 1540\,\mathrm{km}$, $\Omega = 0°$, $\omega = 90°$ for epoch 2020 and both the A/m values is shown in Figure 1. The maps clearly show the presence of resonant corridors, corresponding to well-defined values of initial i, where the time needed to reenter can become significantly lower than the lifetime at nearby inclinations. This resonant behavior can be induced by SRP or lunisolar perturbations or geopotential depending on the initial conditions. Comparing the two maps, we can observe that increasing the A/m value, the resonant effect due to SRP becomes more effective.

This kind of analysis has been further supported and confirmed by the characterization of the orbits in terms of their periodic components. Indeed, by means of a suitable numerical computation of Fourier transforms of the eccentricity temporal series, we were able to find spectral signatures corresponding to the resonant corridors. A theoretical analysis of the resonances involved was performed as well.

Table 1. Grid definition in semi-major axis a, eccentricity e, inclination i, longitude of the ascending node Ω, argument of pericenter ω. R_E is the Earth radius.

Orbital element	range	step
semi-major axis a	$R_E + [500 \div 3000]$ km	$\Delta a = 20,\ 50,\ 100$ km depending on the altitude
eccentricity e	$[0.0001 \div 0.28]$	$\Delta e = 10^{-3}$ up to 0.009; $\Delta e = 10^{-2}$ elsewhere
inclination i	$[0° \div 120°]$	$\Delta i = 2°$
longitude of ascending node Ω	$[0° \div 360°]$	$\Delta\Omega = 90°$
argument of pericenter ω	$[0° \div 360°]$	$\Delta\omega = 90°$



(a) $\Delta\Omega$ = 90°, $\Delta\omega$ = 90°. (b) $\Delta\Omega$ = 90°, $\Delta\omega$ = 270°. (c) $\Delta\Omega$ = 180°, $\Delta\omega$ = 90°. (d) $\Delta\Omega$ = 180°, $\Delta\omega$ = 270°.

Figure 2. Sup-e maps of the MEO phase space for i = 54°, for epoch 2020, and for two effective area-to-mass ratios (m^2 /kg), 0.015 (top) and 1 (bottom). The colorbar is from eccentricity 0 to 0.8.

In the MEO region a broad scan of the GNSS (high inclination regions) and GTO dynamical environments, in both the a - e and Ω - ω phase spaces (see Tsiganis *et al.* in this volume) was performed. The complex resonant structure of this region of the circumterrestrial space was clearly identified, along with the chaotic regions stemming from the phenomenon of resonance overlapping, as identified in previous studies ([6], [7], [4]). The lunisolar secular resonances furnish a number of interesting disposal hatches at moderate and low eccentricity orbits for the GPS and Galileo inclinations (see, e.g., Fig. 2). Note that, depending on the choice of orbital plane and, rather critically, on the choice of initial orientation angles, lifetimes as short as ~ 40 years can occur for eccentricities smaller than ~ 0.15. For the critically inclined GLONASS constellation, the disposal regions generally occur at higher eccentricities, which would make it much harder to actually use. Note that, at all constellation inclinations, solar radiation pressure serves to widen the reentry regions, but without deforming them considerably.

Long term perturbation analysis was performed also for GEO region (see Colombo et al. in this volume) considering the effect of luni/solar perturbation, solar radiation pressure, and a 5x5 gravity field with the semi-analytical long-term orbit propagator PlanODyn [2]. Initial conditions around the GEO altitude were considered with a range of eccentricity from 0 to 0.9 and inclinations of 0-90 degrees. The standard GEO region (small eccentricity, small inclination) does not show high oscillations in the eccentricity, which means that natural re-entry disposal solutions are not possible. However the maps can better direct the choice of graveyard solution, i.e. orbit with small eccentricity (less than 0.005), perigee altitude above the GEO ring (as suggested by the ESA and IADC guidelines), but also the choice of latitude can be taken into account for ensuring a long term stability of the orbit. For higher inclinations (above 50 degrees) and small

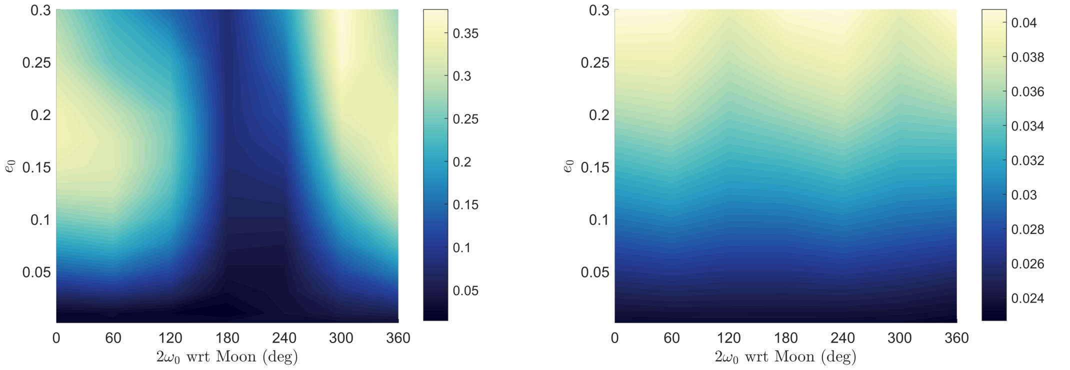


*Figure 3. Δe over 30 years for initial orbit with $a = a_{GEO}$ and initial eccentricity between [0 0.3]. Left: Initial inclination of 0 degrees and CR*A/m=0.012 m2/kg. Right: Initial inclination of $35°$ and $C_R A/m = 1$ m^2/kg.*

eccentricities, re-entry is possible over the time span of 60 years. This is the case of the Chinese BeiDou constellation. As an example Fig. 3 shows the maximum variation of the eccentricity over 30 years simulation for initial orbits with $a = a_{GEO}$ and initial eccentricity between 0 and 0.3 for (a) initial inclination of zero degrees for a satellite with $C_R A/m = 0.012$ m^2/kg and (b) initial inclination of $65°$ for a satellite with $C_R A/m = 1$ m^2/kg. With respect to the case of satellite with lower value of $C_R A/m = 0.012$ m^2/kg, in the enhanced SRP case the oscillation in eccentricity are more pronounced. Moreover at high inclination the luni-solar resonance become evident. The use of solar sails for enhancing the effect of the natural dynamics is also under analysis. Different strategies of sail attitude control (active control and passively stabilised sail) were investigated [3]. The passive stabilised sail was selected as requiring a smaller control on the sail. The required sail dimension was calculated for all the initial conditions from LEO to GEO in terms of the required area-to-mass ratio to deorbit. The effect of a sail is in general to extend the amplitude of the oscillations in eccentricity and therefore to enhance the natural re-entry disposal. As example Fig. 4 shows the sail requirements for deorbiting from a slightly eccentric orbit at different semi-major axis in 5 year time.

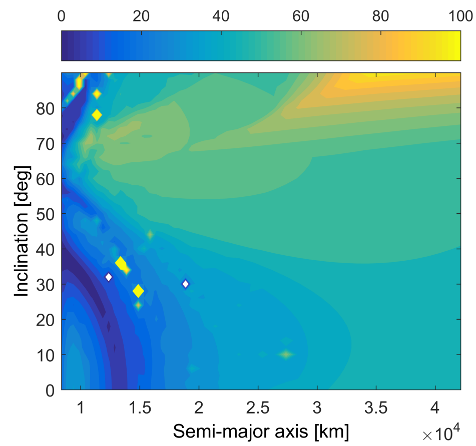


Figure 4. Area-to-mass times reflectivity coefficient [m^2/kg] to de-orbit from a 0.2 eccentricity orbit and $\Omega_0 = 0$ degrees with sail passive mode strategy.

4. DESIGN AND 3D PRINTING

The design phase, including 3D printing, shielding and design for demise has started. The facilities for 3D printing and testing have been identified and classified. The main spacecraft parts that shall be 3D printed for the testing phase were agreed upon by the involved partners. The set up and the experimental samples for the wind tunnel facility tests were identified and are under preparation.

In order to obtain information about the technologies to be developed in the project an analysis of the state of the art was initially carried out. The main activities and findings are outlined here

- Review of End-of-Life (EoL) Concepts and Technologies. The EoL concepts and technologies were identified and the state of the art was reviewed. An in depth analysis of the technology was performed.
- Review of common spacecraft designs for representative applications, analysing the spacecraft design from a holistic point of view, considering well known applications such as Earth Observation and telecommunications;
- Review of 3D printing technologies and materials. The state of the art of 3D printing technologies and how they are applied to satellite components and

structures was analysed. It is noted that, to apply 3D printing in some components and structures, they have to be redesigned and optimized. According to this analysis, ReDSHIFT shall focus on space components that can be 3D printed, such as: primary structure, multifunctional structures and deployable structures.

- Analysis of Shielding Concepts for Non-Catastrophic Impact, pointing out the need to keep the mass and volume within tight constraints, although this limits the ability to protect against large particles. The focus should be on multi-wall concepts which have the greatest potential, at the same time maintain a holistic design approach through multi-function panels, reducing the mass and volume of the shielding.
- Shielding Concepts for Catastrophic Impact. This discipline is still at low Technology Readiness Level (TRL). Hence there is the need to analyse alternative shielding designs, making use of local discontinuities and predetermined fault lines in the materials. Breakup modeling (to be performed in the coming years) is thought to be key. The goal here is to combine the existing algorithms and methods through an innovative approach, reaching a useful tool to explore new technology solutions to support design activities and support design for demise.
- Design for demise. There is the need for further research work in order to develop and test the tools and the guidelines for spacecraft design, to guarantee that there is no re-entry of spacecraft components and parts (casualty risk).

For each of the reviewed technology the TRL was assessed, leading all the partners to decide which one of these technologies will require additional research during the next stage of the project and how this will affect the design and development of the planned systems. In this way, the Technology Roadmap of the project was defined.

The overall plan of 3D design and printing is now settled. It cannot yet be disseminated here, but it will be publicized in due time with the advancement of the project.

A programme of work is being defined to investigate the design and evaluate the performance of at least three different types of unmanned spacecraft shield which might be manufactured using 3D printing. Further details on this subject will be disseminated in the next stages of the project.

Concerning the design of EoL technologies, most of the efforts are concentrated on solar (and drag) sail technologies, especially for sail containers and for the sail module attach mechanism.

In the design-for-demise (D4D), the overall objective was the definition and trade-off of demise concepts for 3D-printed spacecraft. The interaction with de-orbiting highways and the implications for D4D due to different re-entry conditions was assessed. This analysis found that the trade-off between the re-entry speed and steepness results in reduced demise for re-entries from high LEO and MEO relative to a decaying circular orbit re-entry. The interaction with spacecraft structures and the assessment of feasibility of break-up planes was performed. The priorities for the tests to be performed in the arc-heated wind tunnel at DLR were established. The tests will be performed in the coming months of 2017 and the results will be disseminated once completed.

5. SOFTWARE DEVELOPMENT

A complex software, encompassing all the findings of the project will be one of the final products. It will provide a complete debris mitigation analysis of a mission, using existing debris evolution models and lessons learned from theoretical and experimental work. It will output safe, scalable and cost-effective satellite and mission designs in response to operational constraints. The software design is now completed, the general architecture and all the modules are defined.

The ReDSHIFT tool has been conceived as a suite, i.e. different independent and specialized software modules which will be integrated in a single framework to be distributed within the consortium. A web-based interface will be also provided to give access to a simplified version of the suite for public access. By addressing the analysis of the debris environment, the disposal and mitigation strategies, the re-entry and demise solutions and the protection design, the tool will provide a comparative assessment of the technologies and the disposal strategies that can be conceived for current and future missions. Given the specifics of the mission, in terms of orbit, propulsion system, operational and economic constraints, the software will give the optimal EoL plan to be adopted. The output will concern dynamical and technology issues, with the distinction between satellites already in orbit and future ones. The trajectory optimisation will be performed by taking into account several aspects: attitude-orbit coupling, on-board propulsion devices, manoeuvrability and visibility, and the role of the unknown parameters on the orbit evolution. The tool will indicate the best natural path to be followed, and the best propulsion system (among the ones available) which could assist the feasibility of the disposal. For future missions, a trade-off between EoL strategy and operational orbit requirements will be given. The choice of the best trajectory among the feasible ones will be made also considering the impact on the background population, in terms of collision risk and long-term evolution, by simulating different scenarios. Each possible strategy will be ranked also according to the survivability of the spacecraft during operations and disposal, the footprint in case of re-entry, and the compliance with the current mitigation guidelines. Finally, the software will estimate the optimal design for protection shielding and design-for-demise, pointing out the actual technology readiness, the corresponding development cost and economical return.

The ReDSHIFT software will be a suite of independent tools, each one developed by a unique team and then integrated by an independent one into the OpenSF framework. OpenSF is a generic and open source simulation framework distributed and maintained by the European Space Agency (further information can be found in the ESA Earth Observation Portal, http://eop-cfi.esa.int/index.php/opensf). It provides end-to-end simulation capabilities that allow assessment of the science and engineering goals with respect to the mission requirements.

The current design foresees the following SW modules:

- Environment Projection: this module aims at providing a number of future evolution scenarios, pre-simulated with the long term evolution tools mentioned in Sec. 2. The scenarios should be mainly used, inside the general software, to compute fluxes against the spacecraft selected by the user. The population files including the characteristics (e.g., area and mass) and the orbital parameters of all the objects, are produced off-line during the simulations described in Sec. 2 and are read by the current module to produce the flux/collision risk output. The possibility to compare the output of different scenarios is envisaged. The module should be properly interfaced with the Disposal Mapping module to allow also the computation of the expected collisional flux on the disposed spacecraft along the selected disposal trajectory.
- Flux and Collision Probability Module: strictly related to the previous one, this module provides a lightweight version of the long-term simulations for flux calculation and collision probability calculation. It is derived from the main long term evolution softwares, but uses only a specialized subset of those functionalities.
- Disposal Mapping: this module is aimed at providing the user with the best disposal strategy (i.e., orbit) in different orbital regimes (from LEO to GEO). To this aim, different EoL disposal strategies shall be tested and compared. The main component of the module will be a number of "maps" of the phase space indicating, for each orbital regime, the most convenient locations (in terms of the Keplerian orbital elements) where a spacecraft should be moved at end-of-life, to minimize its residual orbital lifetime or, conversely, to maximize its stability in that specific orbital altitude (e.g., in the case of the GEO graveyard orbits). Namely the disposal mapping module will perform the following tasks:
  - Display the maps that characterise the dynamic behaviour of spacecraft orbits from LEO to GEO
  - Provide the stability conditions of such orbits
  - Characterise the natural re-entry time or the stability of a graveyard orbit over a long enough propagation time. The length of this time interval will be defined in WP3.
  - Provide the desirable manoeuvre to accelerate or improve the re-entry or graveyard injection.
  - Assess the disposal strategies in terms of their effects on the debris environment.

  The module should be properly interfaced with the Environment Projection module to allow also the computation of the expected collisional flux on the disposed spacecraft along the selected disposal trajectory.
- Sail dynamics: this module is aimed at characterising the dynamics of a solar sail for de-orbit and its interaction with the space debris population. The analysis of the sail dynamics will be used for performing a preliminary design of the deployable surface. In particular, the name module will perform the following task:
  - Identify the required deployed area for achieving EoL deorbiting for a defined timeframe;
  - Characterise the orbit-attitude coupling during the deorbit;
  - Assess the feasibility of the deorbit through solar radiation pressure augmentation devices (sail or balloons) from the set orbit;
  - Propose a sail design (including packaging);
  - Characterise the interaction of the sail with the debris population.
- Design for Demise Assessment Tool: this module is designed to provide a first order assessment of the casualty risk, as defined by the on-ground casualty area, for a re-entry and to suggest design for demise mitigations to reduce this risk. In doing so it will provide coverage for all entry types, including those associated with "de-orbit highways" as identified within the ReDSHIFT project. The tool will identify the critical components from a catalogue of vehicle elements, given an initial entry condition, and suggest and evaluate strategies to reduce the on-ground casualty risk.
- Space Debris Shielding: this module aims at assessing the shielding performance of different structural panels/shields against the threat given by small (i.e. un-trackable) pieces of debris. The module is based on simplified equations and/or point data given in tabular format which describe the protection effectiveness of common spacecraft walls and innovative shielding concepts developed in the framework of ReDSHIFT (including 3D-printed parts). These equations/data intend to provide a basic description of debris clouds ejected in the spacecraft internal compartments after perforation of the satellite hull.

The high-level system decomposition, with the identified interfaces among the different modules is shown in Fig. 5.

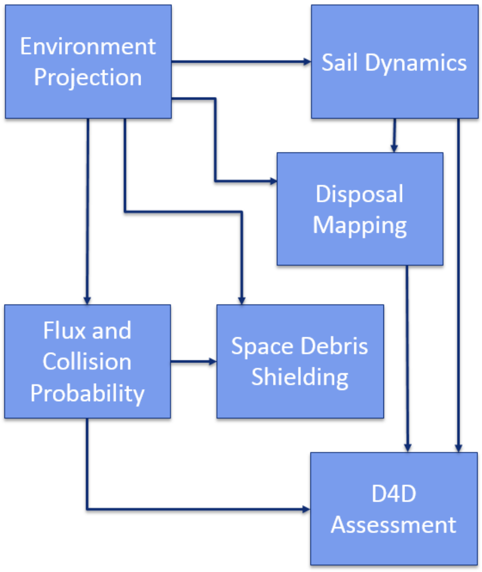


Figure 5. ReDSHIFT Simulator High-level System Decomposition.

6. CONCLUSION AND PERSPECTIVES

The ReDSHIFT project is now well within its second year of activities and all the activities are proceeding as expected. As briefly detailed here, the first results are very promising. The majority of the simulations and theoretical work on astrodynamics is completed, with the analysis and long term environment settled and analysed. The cartography of the phase space was performed, with the identification of the possible "de-orbiting highways". The analysis of the maneuvers to better exploit these de-orbiting solutions is under way and shall be completed by mid 2017. The experimental part of the project is started as well and the design, production and testing of the first 3D printed prototypes is expected by the end of 2017.

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