SATELLITE FAILURE RISK DUE TO HYPERVELOCITY IMPACTS

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ABSTRACT

The increasing accumulation of space debris objects on earth orbits represents a risk for spaceflight missions. Particle impacts on satellites can lead to serious damages or even to the loss of a mission. In this paper the risk for historical and future satellite missions is analyzed separately. For historical satellite missions, the risk analysis is combined with cost estimations. Altogether 3893 satellites were examined and their analysis results evaluated. The failure probability of selected future satellite missions due to hypervelocity impacts from space debris is estimated for the years 2005 and 2055. The future evolution of the spatial density is predicted for a business-as-usual scenario which is based on the launch activity in the years preceding 2005. The predicted evolution of the space debris environment is discussed in terms of object sources and orbit altitudes. The analysis shows that an increase in the failure probability of satellites is likely.

INTRODUCTION

The increasing accumulation of space debris objects on earth orbits represents a risk for spaceflight missions. Particle impacts on satellites can lead to serious damages or even to the loss of a mission. The development and the production of a satellite are connected with economic expenses for the investor and/or the government. One risk aspect is the loss of the satellite before the nominal end of its mission. This loss can be caused among other things by hypervelocity impacts of debris objects and micrometeoroids. The estimation of the risk and cost due to particle impacts for historic satellite missions is subject of this work. A close look is also taken at the risk for selected satellite missions for the years 2005 and 2055. The failure risk for the year 2055 is estimated based on a business-as-usual development of the space debris environment.

The potential risk of particle impacts is caused by the high kinetic energy that can be released due to the high collision velocities. The probability of a satellite failure is a combination of the risk of hypervelocity impacts, the risk that particles penetrate the satellite hull, and the risk of damage to vital subsystems.

If hypervelocity impacts occur on a satellite, a variety of damages of different type can be expected. Impacts of small particles lead to degradation of the surface of the satellite. Such an external damage is however in most cases not critical for the operation of the satellite.

An impact which leads to a loss of the satellite may occur, if the satellite wall is penetrated. In this case, vulnerable subsystems in the interior of the satellite can be damaged. Particularly critical systems are electronic boxes which are mounted directly on the inner side of the satellite wall. In the following risk analyses, therefore only impacts are considered which penetrate the satellite wall.

Cost Estimation

For the assessment of damage cost, the following procedure is selected. First of all the cost

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

(the value) of each single satellite is estimated. Then a risk analysis is carried out for every satellite, and its failure probability is determined. The value of the satellite is weighted with the failure probability. The result is the damage cost. The cost estimate is made on the level of satellite subsystems. Their masses are used as input parameters for cost models. In a first step, mass models for satellites have been developed based on statistical analyses. With these models, it is possible to estimate the subsystem distribution as a function of the beginning of life (BOL) mass. For each subsystem there exists a cost model which uses the particular system mass as input parameter. The cost of integration and programme is also be taken into account. For all the satellites the same state of development is assumed.

The cost models are based on parametric cost estimation relationships (CERs). CERs determine the cost related to a reference year. This is mostly the year in which the statistical analysis was carried out. Therefore, temporal effects on the cost units must be accounted for. For CERs which will be used for an analysis of a succeeding year, the steady increase of the cost unit (inflation) must be considered. These CERs must be multiplied by a cost inflation factor.

The probability of a satellite failure is estimated by combining the probability of a penetration with a very simple vulnerability model. The failure probability is weighted with the satellite cost, resulting in a probability of loss of amortization. This amortization loss is used as a rough estimation for the cost of damages due to hypervelocity impacts. In this way it is possible to attribute cost to damaging impacts.

Vulnerability

Hypervelocity impacts of particles can damage satellites. There exist no models which can be used to describe the vulnerability of a satellite. Furthermore the different designs of different satellite types impede to determine general criteria for the vulnerability. One can try solely to define plausible criteria. The risk analysis is based on the assumption that only those particles can cause the loss of a satellite mission which penetrate the satellite wall. This simplifying assumption leads to the consequence that several physical effects are not considered. These effects are spallation, electrostatic discharge, electromagnetic radiation and momentum transfer.

The following simplified definition for the damage of an impacting particle will be used: Only a particle which penetrates the satellite wall can damage a satellite. Other effects are not considered. Also satellite anomalies in the case of temporary failure are not considered, because they do not result in a loss of the satellite mission. Three different criteria for simple vulnerability models are defined. The criterion for the first model is based on the size of the projectile. It is assumed that the mission of a satellite is lost, if it collides with a one centimeter large object. In a second model, the kinetic energy of the projectile is used as input parameter. It is assumed that the mission of a satellite is lost when it collides with an object, whose kinetic energy exceeds 100,000 J. This energy limit represents a one centimeter aluminum sphere, with an impact velocity of 12 km/s. The third model is also based on the kinetic energy. It takes the robustness of the different subsystems into account. Furthermore the small size particles are considered. The third criterion is described in detail by Wiedemann et al. [4] Its definition is given in the following.

Some subsystems, like the propulsion system and its tanks, are very robust. If a particle penetrates the satellite wall and parts of the projectile or spallation fragments hit a robust subsystem, no failure will occur. Other subsystems, which contain for example computers or communication equipment, are critical and may be damaged by particles. Especially the Guidance, Navigation and Control (GN&C) subsystem is very critical compared to other subsystems, because a failure may result in a loss of the whole satellite mission.

A penetrating particle can cause a damage of the satellite with a certain probability. This may lead to a failure of the entire system. For small projectiles it is assumed is that the particle hits an electronic box. This probability provides a contribution to the overall failure probability of the satellite. The failure probabilities of all impacting particles must be combined to derive a total failure probability.

With the failure of the satellite, a loss of amortization is associated. An early failure would mean a loss of almost all satellite investment cost. A late loss is only a low risk for the investor. It is therefore assumed that the possible point of time of a failure due to hypervelocity impacts is equally distributed over the entire mission duration, so the amount of the amortization loss is 50 % of the damage cost.

SIMULATION OF HISTORIC POPULATION

For the simulation, some assumptions are defined which are the same for all satellites. All satellites have the same lifetime (7 years), the same development status (TRL=7), and the same wall design. The satellite wall is designed as honeycomb structure. The front face-sheet and the rear face-sheet have an identical sheet thickness of 0.4 mm. The spacing between the sheets is 3 cm.

In contrast, it is considered that satellites have different orbits, cross-sectional areas, and costs. The cost model uses real dollar as unit. For every single satellite, a debris (resp. debris and micrometeoroid) risk analysis is performed, the failure probability is calculated, and the damage costs are estimated.

Software Development

The developed software package includes two programs, cost analysis and risk analysis. Furthermore, the Meteoroid and Space Debris Terrestrial Environment Reference Model (MASTER-2005) is used to determine the particle environment [2].

To estimate the cost of a satellite, a parametric cost model was implemented. The key parameter and cost driver is the BOL mass of the satellite. The program determines at first the subsystem masses, then the respective costs. For each type of subsystem, a subroutine is called in which a cost estimation relationship (CER) is implemented. After the costs of the satellite have been modeled, the risk can be determined. The aim is to determine the probability of the satellite loss, because of hypervelocity impacts of particles.

For the analysis of the impact of particles on a satellite, the software tool MASTER-2005 is used. At the beginning of the risk analysis, MASTER is executed to determine the particle environment the satellite is exposed to. For each satellite, unique data files are generated for all analyzed particle sources. These files contain all passages of particles through the selected orbital volume. This data is analyzed. The run time of the software depends on the size of these files.

From the BOL mass of a satellite, an approximate cross-sectional area of the satellite body is derived. The main part of the analysis is the processing of the data files which have been generated by MASTER-2005. The software processes all particle source files. The data of every simulated particle is included in one line. The data used for the analysis is for example particle impact velocity, mass, diameter, flux contribution, etc. Ballistic limit equations are used, to calculate, if an impacting particle will penetrate the satellite wall. According to the selected vulnerability model, a damage probability is attributed to each particle. The contribution of each particle is added successively to the total failure probability. After processing all lines in all data files, the failure probability for one satellite is written to an external file, and the whole procedure is repeated for the next satellite.

In this work, a risk-cost analysis is performed for all historical satellites up to December 31, 2004. Altogether 3893 satellites are considered (see Figure1). (Manned spacecraft are excluded.)

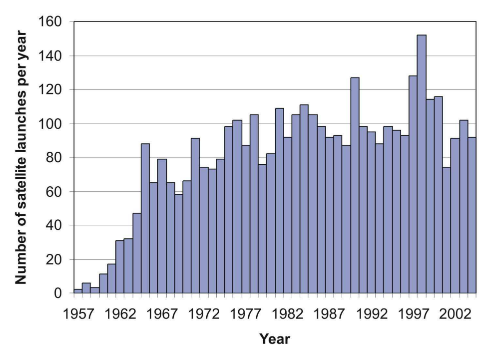

Figure 1. Launch rate of satellites (unmanned spacecraft) up to December 31, 2004.

HISTORICAL DAMAGE COST

The vulnerability of a satellite is defined in a very simple way and is based solely on plausible assumptions [5]. Using these criteria, simulation runs are carried out to determine the risk. It is investigated, to which risk all historical satellites have been exposed. The risk is expressed as a financial loss. The financial loss is expressed in terms of accumulated depreciation, summed up over the years 1957 to the end of 2004.

The vulnerability model used here is based on the kinetic energy. Objects, which impact with an energy of 100,000 J, cause the loss of the satellite. In this case the failure probability is 100 %. For a particle with a lower kinetic energy, the failure probability is reduced in a direct proportional way; i.e., a penetrating particle with a kinetic energy of for example 10,000 J leads to a failure probability of only 10 %.

There is the question, whether a linear reduction of the failure probability as a function of the kinetic energy can be a suitable damage criterion. Currently there exist no vulnerability models which allow the estimation of the failure probability for satellite subsystems. The model selected here is based upon the acceptance that particles with low kinetic energy also cause lower damages. One must however bear in mind, that various types of impact damage exist. The very high impact rates of small particles can lead to numerous types of anomalies which are not considered by the current vulnerability model. These anomalies comprise for example momentum transfer, triggering of electrostatic discharge, plasma generation, spallation etc. Many of these anomalies can appear, if the large solar arrays are hit. All of these effects can lead to damages which are not simulated here. It is therefore possible that the effect of the small particles is underestimated. The main goal of the simulation is to demonstrate that it is possible to consider also small particles. The simulation is very time consuming due to the extraordinarily high amount of small size particles. The result is shown in Figure 2.

The results show that the total damage costs for all satellites up to the year 2004 are 650 MS$. The damage costs caused by debris objects alone are 550 MS$.

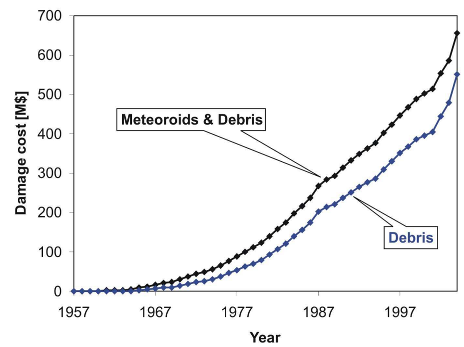

Figure 2. Cumulated damage cost of all 3893 historical satellite missions expressed in real dollar. (Man-rated spacecraft are excluded.)

FUTURE FAILURE RISK

The following section exemplifies the influence of a satellite's orbit and the flux level within that orbit on the failure risk. In addition, an outlook on the possible development of the satellite failure risk within the next 50 years is made. To this end, three orbit types are analyzed for the years 2005 and 2055 respectively. The orbit types are given in Table 1.

Table 1. Orbit types; a - semi-major axis; i - inclination; e - eccentricity

Orbit type	a [km]	i [deg]	e [-]
LEO SSO	7271	98	0
GEO	42,164	0	0
GPS	26,552	62.5	0.007

The following model parameters are chosen: The total mission time for each case is seven years. In order to estimate the failure probability for the entire mission, the annual object flux onto the satellite is multiplied by the mission duration. The satellite walls are modeled as honeycomb sandwich structures. The bumper and back wall of the double wall construction both have a thickness of 0.4 mm. The spacing between the two sheets is 10 mm.

Future Space Debris Population

In order to determine the failure probability of satellites for future epochs, a population must first be established. This population is generated based on business-as-usual assumptions using the software tool LUCA. The Long Term Utility for Collision Analysis (LUCA) is a software which is developed at the Institute of Aerospace Systems of the Technische Universität Braunschweig to predict the future evolution of the space debris environment and the future rate of collisions. In this study, launch and mission related objects (LMRO), solid rocket motor slag (SRMS), Sodium-Potassium droplets (NaK), explosion fragments (EXPL) and collision fragments (COLL) are taken into account for diameters above 1 mm.

The definition of the business-as-usual scenario is based on historical data. The production rates for payloads, rocket bodies and mission related objects given in Table 2 are based on the scenario definition of the business-as-usual scenario as given in the MASTER-2005 final report [2]. The production rates were defined by QinetiQ based on the DISCOS database for the years 1997 to 2004 inclusive. The production rate of solid rocket motor slag is based on an analysis of the firing rate between 2000 and 2004 inclusive. This time frame was chosen rather than including the years 1997 to 1999 as the use of solid rocket motors has decreased noticeably in recent years [3] and averaging over the larger time interval would not have been representative of a business-as-usual scenario. The rate of explosion events is based on the events in the time frame of May 1997 to May 2005 inclusive based on the events given in the MASTER-2005 final report. In addition to the annual production rates, a look was taken at mitigation measures which are currently being implemented. According to the *Classification of Geosynchronous Objects* published by ESOC, a significant number of geostationary satellites are being successfully reorbited to a graveyard orbit on an annual basis. For the years 2004 to 2007, an average of 5 to 6 geostationary satellites have been successfully reorbited annually. A maneuver was rated a success if the resulting orbital height was increased to an altitude which is in line with the IADC Space Debris Mitigation Guidelines [1].

The future debris population used in the current paper is of yet an intermediate result. The population was created without averaging over several simulation runs. This results in an unsteady development of the debris sources over time especially for the sparsely populated GEO region. This will be seen in the following section. In the further work within the project, the scenario definition will be refined and Monte-Carlo runs will be performed. The current results should therefore be viewed as preliminary.

Object/Event type	Annual rate	End-of-Life re-orbiting
Payloads (LEO/MEO)	58	-
Payloads (GEO)	25	5.7
Rocket Bodies	69	-
Mission Related Objects	115	-
SRM Firings (LEO/MEO)	9	-
SRM Firings (GEO)	1.8	-
Explosion Events	5.7	-

Table 2. Definition of the Business-as-Usual Scenario

FUTURE SPATIAL OBJECT DENSITY

The simulated spatial object density over time of all simulated sources larger than 1 mm is presented in Figure 3 for the LEO environment up to 2000 km altitude, in Figure 4 for the altitudes 2000 km to 34775 km and in Figure 5 for the GEO environment between 34775 km and 36775 km altitude. For the years leading up to 2005, the population from MASTER-2005 is used.

For the LEO environment, all sources show an increasing tendency except for the sodium potassium droplets (NaK) as no additional source exists for these. The stepped reduction of the NaK droplets is due to the solar cycles which cause the atmosphere to expand and contract with a period of approximately 11 years. The changing friction causes the orbital rate of decay to oscillate. For 2005, the highest contribution is from solid rocket motor slag and explosion fragments. The number of in-orbit objects for explosion fragments however increases more quickly than for the solid rocket motor slag. The larger debris objects in turn are a source for additional debris as these collide with each other (feedback collisions) or with operational satellites. The number of collision fragments thus is seen to increase drastically until for the year 2055, the spatial density of collision fragments breaks even with that of explosion fragments.

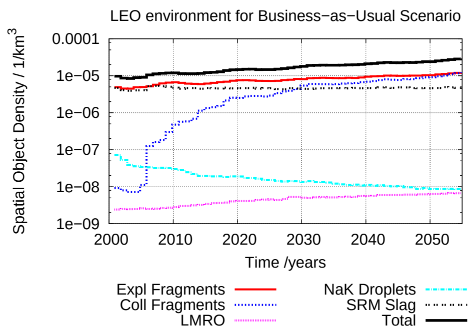

Figure 3. Spatial object density over time for the LEO environemnt below 2000 km altitude for objects > 1 mm.

Figure 4 depicts the development of the spatial object density over time for the MEO environment. Solid rocket motor slag is the major source for debris for these altitudes. All other sources are more than an order of magnitude lower for sizes above 1 mm. Due to the high total volume of the MEO region compared to the LEO region, changes in the spatial object density are much more graduate than for the lower altitude range. Here too however, the collision fragments show a drastic increase with a value just below that of the explosion fragments for 2055. This value is approximately two orders of magnitude below the density from solid rocket motor slag for the same year.

The GEO environment shows an uneven increase in collision fragments. This results from the fact that the population was created from a single simulation run and without Monte-Carlo averaging. It can be seen however that the largest increase also for this region can be expected from collision fragments. All collisions which were simulated with LUCA occur in the LEO region. The fragments which are seen in the GEO region result from a very low number of collisions between LEO objects and objects on highly excentric medium earth orbits. A low number of fragments from these highly excentric orbits thus are carried into the GEO region.

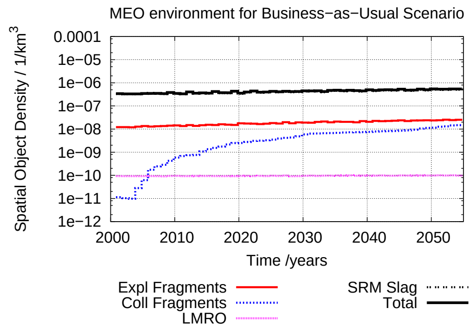

Figure 4. Spatial object density over time for the MEO environemnt between 2000 km and 34775 km altitude for objects > 1 mm.

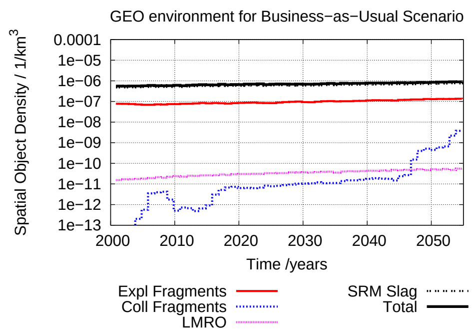

Figure 5. Spatial object density over time for the GEO environemnt between 34775 km and 36775 km altitude for objects > 1 mm.

FUTURE FAILURE PROBABILITY

Figures 6, 7 and 8 show the failure probabilities of the three detailed example missions for the two epochs 2005 and 2055 due to hypervelocity impacts from objects larger than 1 mm.

LEO sun-synchronous orbit

The total failure probability for a satellite on a 900 km sun-synchronous orbit is calculated to be about 3.91 % for 2005 and 8.02 % for 2055 (Figure 6) which is equivalent to an increase by about 105 %. This is mainly the result of the increase in failure probability due to collision

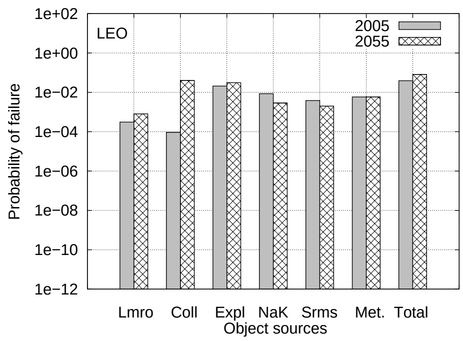

Figure 6. Failure probability of 900 km sun-synchronous satellite from hypervelocity impacts larger than 1 mm. (satellite surface area: 20 m^2, mission lifetime: 7 years)

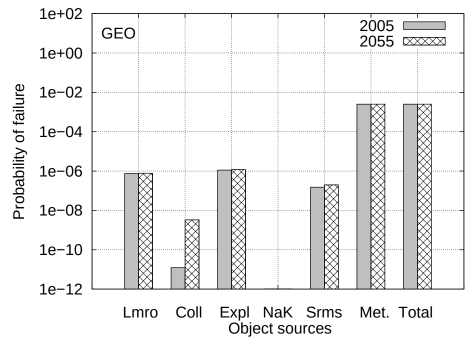

Figure 7. Failure probability of geostationary satellite from hypervelocity impacts larger than 1 mm. (satellite surface area: 20 m^2, mission lifetime: 7 years)

and explosion fragments. The respective tendencies of the failure probabilities can be explained by the development of the spatial object densities for this region. The greatest change is thus seen for collision fragments which show an increase in the failure probability by three orders of magnitude. For 2005, the object types with the largest influence on the total failure probability are explosion fragments, followed by sodium-potassium droplets, meteoroids and solid rocket motor slag. For 2055 the collision fragments have the greatest effect on the total failure probability, followed by explosion fragments, meteoroids, sodium-potassium droplets and solid rocket motor slag.

Geosynchronous orbit

For a satellite on a geosynchronous orbit, a total failure probability of 0.2512 % is determined for 2005 and for 2055 (Figure 7). The failure probability in this region is dominated by impacts from meteoroids and is about 0.2510 %. Launch and mission related objects and explosion fragments contribute with failure probabilities in the order of 10^{-7} and 10^{-6}. Collision objects show the largest increase from 2005 to 2055 by two orders of magnitude.

GPS orbit

As in the case of the geosynchronous orbit, the failure probability for a satellite on a GPS orbit is dominated by impacts from meteoroids. The total failure probability therefore stays roughly constant at 0.274 % and is only slightly higher than that of a geosynchronous satellite. The slightly higher failure probability is however not the result of a higher spatial object density over the GEO region, but can be attributed to the higher collision velocities with space debris particles for the GPS orbit. While operational geostationary satellites orbit the earth at the equator and most other objects have inclination below 15° due to complex perturbative effects, GPS satellites have an inclination of about 62.5 °. The impact angles are therefore centered around an impact azimuth of 85 °. The impact azimuth is measured from the velocity vector, perpendicular to the orbital plane. The most common impact azimuth on GPS orbits in contrast is around 55°, leading to a higher relative velocity for GPS satellits. As solid rocket motor slag is the space debris type with the highest abundance for 2005 and 2055 in both orbital regimes, the effect of the increased impact velocity is highest for these particles. Again, the largest relative increase in failure probability is seen in the collision fragments which increased by almost two orders of magnitude.

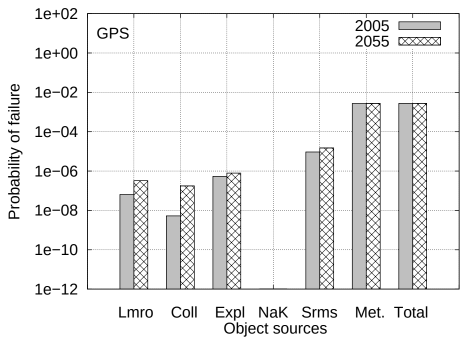

Figure 8. Failure probability of satellite on GPS orbit from hypervelocity impacts larger than 1 mm. (satellite surface area: 20 m^2, mission lifetime: 7 years)

SUMMARY

All described simulations are very complex. Especially the simulation of the historical failure cost is extremely time consuming as an independent risk analysis is performed for about 4000 satellites, including the determination of subsystem distribution, failure probability, and cost estimates. The analysis of the historical satellite population shows variations between 550 M$ and 650 M$ depending on the selected vulnerability model. This cost is equivalent to the value of 5 satellites. Due to the strong simplifications in the definition of the vulnerability of satellites, these numbers should be understood only as estimation of an order of magnitude. The work shows that a risk and cost analysis concerning the interaction of space debris with a high number of satellites is possible.

An initial review has been performed of the influence of the orbit regime and a changing spatial density on the failure probability of satellites. The future population is based on a business-as-usual scenario and was produced without the use of Monte-Carlo runs. The spatial object density of collision fragments for objects larger than 1 mm is currently negligible compared to that of solid rocket motor slag or explosion fragments. The simulation shows however, that within 50 years, collision fragments may become the largest contributor to the space debris population alongside explosion fragments and slag for this size regime. This is especially critical as the creation mechanism for collision fragments can only be influenced indirectly through the reduction of the overall spatial object density. The failure probability for example satellite missions with a mission duration of seven years for 2005 has been estimated at approximately 4 % (LEO), 0.27 % (GPS) and 0.25 % (GEO). For 2055, these probabilities may increase to or beyond 8 % (LEO) while staying constant for GEO and GPS type orbits. For the two higher mission examples, meteoroids pose the greatest risk for failure due to hypervelocity impacts. For the LEO environment, explosion fragments and sodium potassium droplets currently have the largest influence while collision fragments are simulated to have an equal share in 2055.

Future work will use more sophisticated models for the vulnerability and cost estimation. Refined scenarios for the future development of the debris environment will be used and Monte-Carlo simulations in the population production process will be performed for greater statistical reliability of the population.

ACKNOWLEDGMENT

The results presented in this paper were achieved during the research project Analyse zur Deutschen Position zur Wirtschaftlichkeit und Nachhaltigkeit von Space Debris - Vermeidungsmanahmen (50JR0783) of the German Federal Ministry of Economics and Technology, on behalf of the German Aerospace Centre (DLR). All responsibilities for the contents of this publication reside with the authors.

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