Space Sustainability in Martian Orbits — First Insights in a Technical and Regulatory Analysis

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ABSTRACT

Hazards from the outer space environment either natural (space weather and asteroids) or artificial (space debris and the growing number of satellites launched to orbit) pose a rising risk to space flight activities. The awareness for space sustainability and space safety has seen a continuous increase in recent years and does not stop at the Earth's sphere of influence. The first spacefaring nations start thinking about sustainability in cislunar space and the Martian environment. This work deals with the issue of space debris in Martian orbits in the light of planetary protection. A Mars Sustainability Framework has been developed. This includes a study on the orbital and regulatory environment of Mars, long-term propagation of orbits of artificial objects and the two natural moons, and the analysis of objects evolution and first approaches for collision probability computation. With this work, the issue of space debris beyond Earth orbit is analysed at an early stage.

1 INTRODUCTION AND MOTIVATION

Outer space became a fundamental resource to human beings, which needs to be protected to preserve its benefits. Current space flight activities are mainly concentrated in Earth orbits. However, deep space exploration has been of interest to space nations since the dawn of the space age. And in recent years, new initiatives focusing on extraterrestrial exploration have risen again also with focus on Mars. Missions to Mars could not only help in searching for life [1], but also represent a deep interest of human beings to explore and expand. Though most of the space flight activities already respect the Principle of Planetary Protection (PPP) (to avoid forward and backward contamination), debris is produced all over our solar system and beyond (Voyager space probes [2]).
Human-made objects in orbit sooner or later become debris unless they are disposed of right away. Around Earth we are capable of monitoring the orbital environment using telescopes and radars. Reference [3] describes the space situational awareness in Earth's vicinity at its current status and argues for an international cooperation for deep space traffic management. As there is no observation infrastructure in the Martian environment, the position of objects around Mars is only known by telemetry data (if still available). Together with increasing interest in Mars exploration, this raises the question about sustainability. Especially in recent years, sustainable space flight activities became a major point in international discussions. Corresponding guidelines have been established.
It needs to be investigated whether the existing guidelines also apply to Mars, or whether new or different guidelines need to be established. And how would they look like? Would they interfere with existing principles? For that an analysis of the Martian orbital environment is required. What is the current orbital status? What might it look like in some decades from now? Does orbital congestion pose potential risk to the future of Mars exploration?
Until now, questions about space debris beyond Earth orbit mainly addressed the Lagrange points [4], or lunar orbits [5]. However, the orbital debris situation around Mars has not yet been investigated in detail.

This work represents first insights in the topic of Martian sustainability, thus the focus for now lies on space debris and orbital congestion even though sustainability includes much more than that. Section 2 provides an overview of the orbital-, section 3 of the regulatory environment of Mars. A complete framework has been developed for the investigation of the orbital environment around Mars with regard to the problem of space debris, including an atmosphere model and potential break-up modelling. The Martian Sustainability Framework and a perturbation analysis are presented in section 4. The preliminary results are detailed in section 5. The on-going and future work will be addressed in the outlook (section 6).

2 ORBITAL ENVIRONMENT OF MARS

2.1 Historic, current and future launch traffic

Mars is the most Earth-like planet in our solar system. It provides reasonable gravitation, a thin atmosphere and temperature and weather conditions that could eventually enable living conditions through technology in the upcoming century. The peak of Mars' interest was in the 70s, but current plans and ideas indicate an increasing number of future Mars missions. Also, Mars' moons (Phobos and Deimos) are a target of future science missions, and may also serve as communication or infrastructure spots towards human exploration of the red planet [6]. Figure 1 shows the space actors that successfully placed orbiters around Mars in the specific epochs since the dawn of the space age. The dashed bar on the right indicates the planned orbiters to be launched in the 2020s.

It can be seen that there is a slight increase since the 1990s. Here, the emphasis is on the fact that these are only

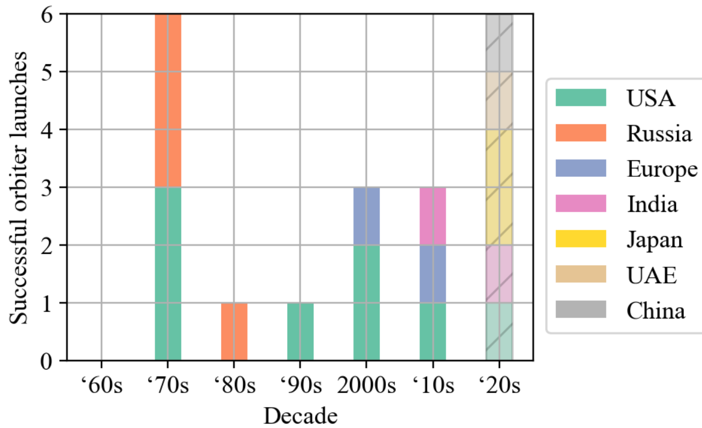

Fig. 1. Successful placement of orbiters in Martian orbit by different states or space agencies over the decades from the 1960s until 2020s.

confirmed figures for the future trends. News and headlines cover many more ideas from small telecommunications orbiters in areostationary orbit (the Mars counterpart of Earth's geostationary orbit) [7] and joint projects for sample return [8] all the way to prepare human settlement on Mars [9]. Also, more and more countries indicate interest in Mars exploration: e.g. the United Arab Emirates [10], Japan [11], China [12] and Finland (just proposal status until now) [13]. The trend of miniaturisation has also been developing for missions to Mars, with recent proposals that include CubeSats [14], [15]. Eight out of 14 orbiting man-made objects in Martian orbit are inactive, so one could say more than half of the population around Mars is already debris. Table 1 compares these numbers with respect to the ones referred to the Earth orbit.

Tab. 1. Satellites in numbers in Earth and Mars orbit, correct information as of January 2019.

	Earth orbit [16]	Mars orbit
Spacecraft placed in orbit since 1957	8,950	14
Number of defunct spacecraft	3,050	8
Debris objects tracked and monitored	22,300	0
Mass in orbit (tons)	> 8,400	< 27

The position of active satellites in Martian environment is known through telemetry data, however the position of by now inactive probes is not known, nor what happened to them after completion of operation. Last available orbit data are considered here for defunct spacecraft and mission-related objects, orbit data from 1st of January 2019 for all active probes. Figure 2 and 3 show the inclinations and eccentricities respectively over semimajor axis for all objects in Mars orbits. These include all orbiters and mission-related objects (e.g. the autonomous propulsion unit (ADU) of Fobos-2, the bioshield bases of the Viking orbiters, MAVEN's break-off cap) [3]. The majority of objects is located in eccentric (0.4-0.9) low Mars orbits (LMO) with inclinations between 30° and 100°. Only a few objects move on circular orbits; only two in the equatorial plane. For better visualisation of all objects, the axes are interrupted. Figure 2 provides a colour code depending on the orbiter mass. Only one orbiter is below 1 ton. So far there are no micro or nano satellites in Mars orbits (no spacecraft up to 150 kg). Figure 3 presents the colour-coded area-to-mass ratio of the objects.

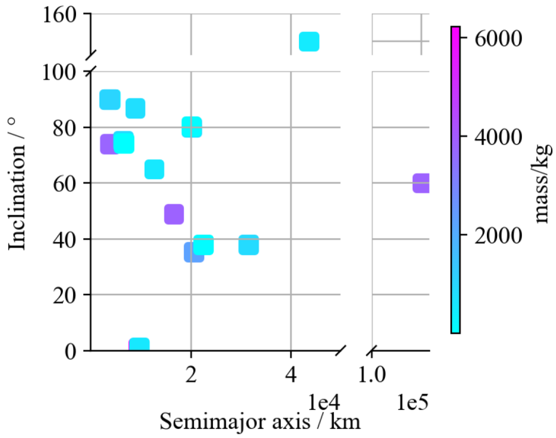

Fig. 2. Inclination over semimajor axis of Mars objects. The colour code indicates the mass.

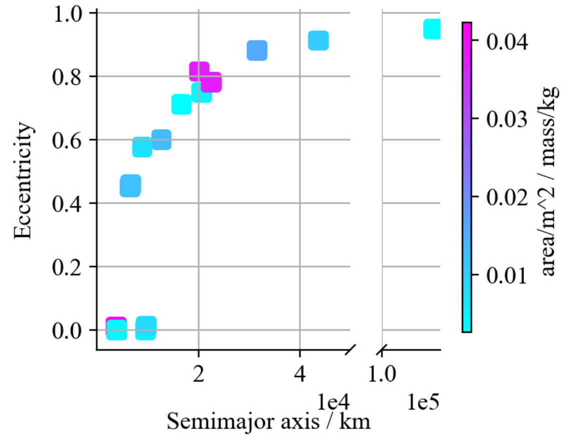

Fig. 3. Eccentricity over semimajor axis of Mars objects. The colour code indicates the area-to-mass ratio.

The different physical and orbital characteristics of Mars lead to a slightly different behaviour of orbiting objects. The smaller gravitational force (at Mars' surface about one third of the Earth's surface gravity field) leads to smaller orbital velocities for similar orbital altitudes (2.8-3.5 km/s in LMO). This becomes important when talking about potential collisions of objects in Martian orbits and the resulting impact velocity. As Mars orbits the Sun in about 1.5 AU distance, the solar radiation pressure is about 45% of the solar radiation pressure in Earth's vicinity. This means that its perturbing effect on trajectories of space objects in orbit around Mars has a different relative importance with respect to Earth orbits. Similar reasoning applies to the effect of atmospheric drag. The Martian atmosphere's surface pressure at mean radius ranges from 4 mbar up to 9 mbar [17] whereas the Earth's atmosphere has 1,013 mbar [18], so the Mars atmosphere is roughly 100-250 times thinner. That leads to a significantly smaller influence of the atmospheric drag on spacecraft trajectories, resulting in about 200 times longer orbital lifetimes compared to Earth satellites at similar height between 300–500 km at peri centre and the same eccentricity e ($e > 0.01$). For circular orbits the lifetime can be 300-800 times longer around Mars for low solar activity [19].

2.2 Space debris sources comparison

Since the launch of Sputnik-1 in 1957, many different sources have led to an increasing number of debris objects in the Earth's orbital environment. Objects have been released either intentionally or unintentionally. The dominating source of new debris objects in Earth orbits, however, are fragmentation events [20]. Not all of these sources need to be considered when examining debris in Mars orbits. According to the NASA Space Science Data Coordinated Archive [21], [22] and [23] all Mars probes have liquid fuel engines. Thus, solid rocket motor firings do not need to be considered for now. Some debris sources are historic and non-reproducing like the released droplets of a sodium-potassium alloy (NaK) and the unintentional cluster forming of the "Westford Needles" [20]. However, the harsh environment becomes noteworthy for debris analysis. Degradation effects through atomic oxygen in higher atmospheres, extreme ultraviolet radiation and impacts of microscopic particles also occur in Martian environment. According to the study presented in [24], the detrimental effect on spacecraft in Mars orbits needs further testing and investigation. Sensor surfaces showed changes in simulated LMO not known from low Earth orbit environment. What that means for degradation products, the generation of paint flakes from spacecraft coatings for example, needs to be investigated. According to [20], resulting paint flakes are of micrometre to millimetre size. For this first analysis particles of this size are neglected but they may become part of future considerations. The impact of small debris particles at high velocities can generate so-called ejecta, more debris particles. The ejecta model adapted and implemented for the MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) environment is applicable for impact velocities from 1 km/s [25]. So, this model also becomes relevant for debris analysis around Mars. The model's application condition states that the projectile diameter needs to be between 5 μm to 1 mm. In addition to the debris from human-made objects in outer space, the meteoroid environment needs to be considered for the long-term degradation of spacecraft surfaces and ejecta generation. This is not part of this work here. Table 2 presents a comparison of debris sources in Earth and Mars orbit and the implementation of the latter in this work.

Tab. 2. Debris sources comparison for Earth and Mars orbits and the implementation in this work.

	Earth	Mars	Considered in this work
Inactive spacecraft	✓	✓	✓
Released payload related objects	✓	likely	×
Lost objects by astronauts	✓	not yet	×
Fragmentation through break-up events	✓	unknown	✓[1]
Fragmentation through collision events	✓	unknown	×
NaK droplets	✓	×	×
Westford Needles	✓	×	×
Degradation products	✓	likely	×
Ejecta	✓	likely	×

3 REGULATORY ENVIRONMENT FOR DEBRIS AROUND MARS

Today, orbital congestion is a recognised danger for the safe operation of space objects and the preservation of the benefit of space flight for humans on Earth. The era of law-making in the 1960s led to laws of a fundamental principle character. The end-of-life of space missions and with that the behavioural aspects of disposal strategies have not been detailed at that time. Nevertheless, the idea is expressed that space activities in outer space including all celestial bodies should be carried out in a protected manner and any interference with the potential of harm to other state's activities should be avoided [26]. Article IX of the Outer Space Treaty (OST) contains the premise of "no harmful contamination" and [27] states that "space debris are a form of harmful interference". There is no international legally binding obligation to implement space debris measures [26], however, it provides a basis for the debris discussion (in Earth and so in Mars orbits). The problem was then discussed and investigated by the Inter-Agency Space Debris Coordination Committee (IADC), founded in 1993. The resulting IADC space debris mitigation guidelines are now recognized by an increasing number of space-faring states and non-governmental actors. Upon that, more and more states implemented space debris mitigation measures in their national space legislation [28]. That represents the transformation of non-legally binding recommendations to a legally binding status.

In 2018, the member states of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) agreed on 21 guidelines produced by the in 2010 established Working Group on the Long-Term Sustainability (LTS) of Outer Space Activities, covering also a part about space debris and space operation [29]. Are the existing policies, guidelines, standards applicable for Martian debris? Guideline B.1 paragraph 3 for example states that space nations should voluntarily exchange relevant information about space objects in near-Earth environment with potential of risking safe space operations [30]. Does that mean the exclusion of the near-Mars environment?

Furthermore, the IADC guidelines, are applicable for spacecraft "injected into Earth orbit" [31]. Space faring states, space agencies and other actors have the freedom to adopt the fundamental principles of these guidelines (or others) in their own standards and regulatory framework in their level of detail. NASA's "Process of Limiting Orbital

[1] hypothetically triggered

Debris" already encourages operators to limit the amount of debris release in Martian environment [5]. The Master's thesis being the basis for this paper will contain a more detailed analysis of different standards and guidelines towards their application potential for Mars and whether these would interfere with existing principles. An example is described here. IADC guideline 5.3.2 addresses Post Mission Disposal in low Earth orbits. It is stated that space objects should be placed or left in an orbit with limited lifetime of up to 25 years after completion of operation. This guideline applied to objects in Mars orbit could interfere with the principle of Planetary Protection. The Committee on Space Research (COSPAR) defined categories for celestial bodies depending on the mission purpose and scientific goal. Orbiter missions around Mars are therefore classified as Category III [32]. The categories define restricted bioburden levels that spacecrafts or landing systems should comply to. This translates to orbital lifetime requirements for Mars probes of 1% and 5% impacting probability for 20 years and 50 years respectively after launch [33]. So, would the 25 years rule prescribed by the IADC guidelines interfere here? Another disposal measure is formulated in IADC guideline 5.3.1 and recommends manoeuvring satellites in geosynchronous region after their end of operation to a higher graveyard orbit. Even if it was applicable to Martian satellites in areostationary orbit, would it be necessary to implement it in a potential future regulatory framework, as currently there are no objects in that region around Mars? These questions will be tackled in the upcoming work.

4 MARS SUSTAINABILITY FRAMEWORK

The developed framework includes a perturbation analysis and the Long-term Evolution Analysis of the Martian Environment Suite (LEAMES).

4.1 Perturbation analysis

The motion of spacecraft around a central body is often simplified to follow unperturbed Keplerian orbits for rough calculations or illustrative purposes. Neither Earth, nor Mars are perfect spheres but have the shape of an oblate spheroid, which leads to gravitational perturbations. As mentioned, other important contributions affecting the satellite's orbit are the atmospheric drag, luni-solar perturbations and solar radiation pressure. In order to study the effect of different perturbations and their relevance for the long-term orbital evolution in LEAMES, they have been formulated as functions of the orbit altitude. The two-body acceleration and the more complex geopotential up to J4 are considered. Third-body perturbations are computed for the Sun, Earth and Jupiter. For Earth and Jupiter, the close approach to Mars is considered. The distance from Sun, Earth and Jupiter to the satellite on its orbit around Mars is simplified to be constant for one orbital revolution of the satellite. That does not apply to the moons Phobos and Deimos. They orbit Mars in LMO and high Mars orbit (HMO) respectively. This requires the analysis of the non-constant contribution of the moons to objects in orbit. However, to provide a simple way to calculate the perturbing influence, Phobos and Deimos are considered to orbit Mars in alignment to the satellites as close companions. This should at least allow for an analysis of an extreme of the perturbations by the moons. For the atmospheric drag a model with coefficients gained by the atmosphere modelling presented in section 4.3 is used. The solar radiation pressure is exemplary calculated for a sphere with the drag coefficient set to 1.3 to represent a mixture of reflecting and absorbing properties.

Figure 4 presents the order of magnitudes of the calculated perturbation accelerations. The drag force is the dominating force up to 30 km, which is then defined as the re-entry point for satellite lifetime analysis. Even the simplified constant contribution of the moons' perturbations is negligible if not orbiting very close to them. Only few satellites have the potential of crossing the moons' paths. Therefore, it depends on the actual orbit design whether the moons have a relevant influence. LEAMES therefore treats the moons just as natural satellites orbiting Mars, no third body acceleration by Phobos and Deimos is included for now but will be part of future investigations in order to examine also different disposal strategies. The occurring perturbation through J4 is more relevant to the satellite motion than solar radiation pressure is up to around 8,000 km. Higher-degree zonal coefficients are not considered. The fact that only secular perturbations are considered in LEAMES, as periodic variations are not of interest for this first insight, lead to the neglect of tesseral or sectoral coefficients. The third-body forces by Earth and Jupiter become only interesting for spacecraft in HMO or high elliptical orbits (HEO) with very high apogees. This will be part of further development of LEAMES in the future. The solar radiation pressure is small compared to the gravitational and atmospheric force, but because of its simple implementation, it is included in LEAMES.

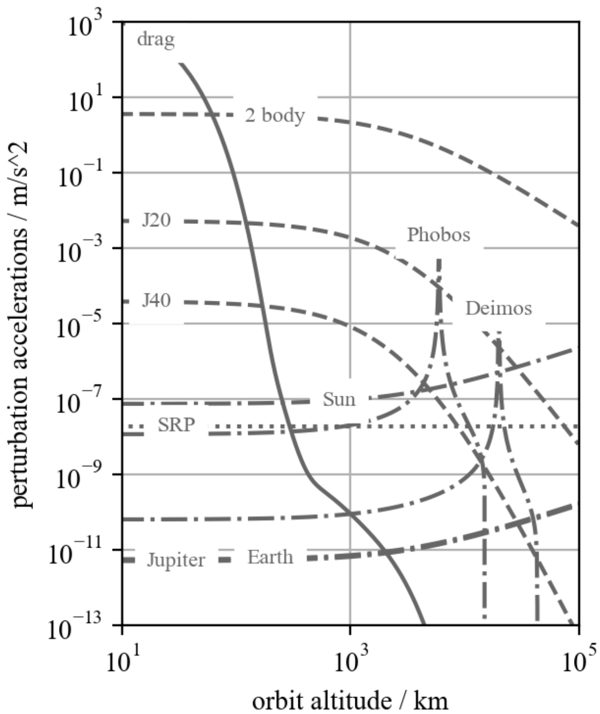

Fig. 4. Order of magnitude of various perturbations acting on probes in Mars orbits as a function of geoid surface distance.

4.2 LEAMES structure

LEAMES is a collection of tools written in Python for the analysis of the long-term behaviour and evolution of space objects in Martian orbits. Its structure is presented in Fig. 5. The core module is the Evolution Model (EM) that includes the Lifetime Analysis Module and the Orbit Evolution Module. EM calls the Long-term Integrator of Mean orbital Elements (LIME) that has been developed for this work, the Break-Up Model (BUM) and the Launch Traffic Model (LTM). User defined settings address the propagation duration, the launch traffic and the break-up rate, and the potential execution of a PPP manoeuvre.

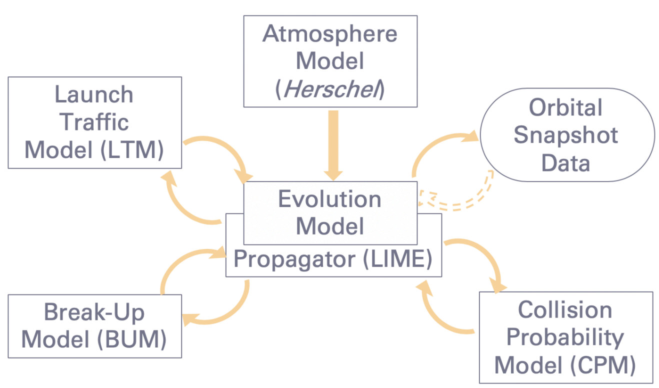

Fig. 5. Structure of the Long-term Evolution Analysis of Martian Environment Suite.

4.3 Martian atmosphere model (Herschel)

For this work, a new frame for Martian atmosphere density modelling based on the Mars Climate Database (MCD) [36] has been developed. MCD offers a wide range of variations in terms of climate and solar radiation, longitude and latitude, and distance from the centre or surface of Mars. Three different atmospheric modelling approaches were applied to the data: simple exponential density profile (EDP), patched exponential density profile (PEDP) and superimposed exponential density profile (SIDP). All three base on the barometric equation, EDP with constant and varying scale height. Although an EDP is characterised by simplicity and low computational effort, the model's increasing deviation from the atmospheric data over a larger range of altitudes leads to large errors in the long-term propagation. PEDP describes a combination of several EDPs with constant scale heights in sequential valid altitude intervals. However, the continuity of the data at the transitions of the individual intervals must be ensured. Moreover, the PEDP may cause difficulties when integrating perturbating accelerations over a full revolution of a satellite on a high eccentric orbit. Analytical formulations derived by King-Hele [19] require an examination of the density profile once before the computation. Using a PEDP for high eccentric orbits with large semimajor axes would span over multiple height intervals. This problem was addressed in [37], where a SIDP is derived by superimposing several partial exponential atmospheres with constant scale heights. Each of the partial ones and the superimposed atmosphere is valid over the whole altitude range. The superimposed scale height is calculated through the superimposed density divided by its derivative with respect to the altitude. The approach of the superimposed King-Hele was adopted here and a new atmosphere model for orbital evolution analysis of Mars satellites developed. The model is called Herschel atmosphere to pay tribute to Sir William Herschel, who was one of the first to postulate the weak atmosphere of Mars [38]. The formulas were applied and fitted to MCD data varied over: -180° to 180° in longitude and from -90° to 90° in latitude, 13 km to 500 km altitude, each for minimum, average and maximum solar EUV conditions and a dust storm. Figure 6 presents a comparison of different atmosphere models created and the varied MCD data indicated in light red. Average Sun radiation and dust conditions are chosen. The Herschel atmosphere and the PEDM match the data from MCD well, whereas the EDM with constant and variable scale height differ up to several order of magnitudes. Even though using the EDM would be most advantageous regarding computational effort, the error becomes too large for long-term orbit propagations. PEDM cannot be used for the semi-analytical approach for the rate of change due to drag in LIME, however the optimisation yields good results for the atmospheric modelling.

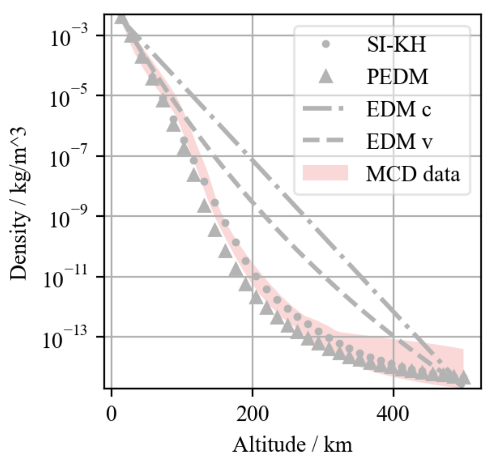

Fig. 6. Overview of different atmospheric models and the raw density data varied over longitude and latitude for average solar radiation and dust conditions produced by MCD.

4.4 Break-up model

Fragmentation events are the dominant source for space debris in LEO, maybe also in LMO. As described above no monitoring of inactive satellites is possible for now, break-ups or collision may already have happened. Therefore, the 1998 NASA break-up model [39] is implemented here. The mass conservation approach proposed in [40] was applied, stating the generated fragments to follow a power law between 1 mm and 1 m and 2-8 fragments larger than 1 m. The maximum dimensions of the satellites are respected. Mass conservation is also regarded for the case the fragment cloud is too heavy (potential case for an explosion of a CubeSat sized object). In the latter the largest fragments are removed until the exploding object mass is met again. In terms of limiting the computational effort for the long-term propagation in LEAMES the number of fragments to be propagated will be cut at the minimum size causing a catastrophic collision (a specific energy of 40 J/g at the centre of mass of collision is considered here) with the Martian satellites. Although particles being in the micrometre and millimetre size regime have damage potential, this is not considered for now.

4.5 Long-term Integrator of Mean orbital Elements (LIME)

LIME is a semi-analytical propagator for satellites in Martian environment. The secular rates of change due to the Sun, drag, the complex gravitational potential of Mars up to J4 and solar radiation pressure are calculated analytically. They are then integrated numerically with the fixed time step of one orbital revolution using either Euler's method or the Runge-Kutta method (RK45).

5 PRELIMINARY RESULTS

The preliminary results obtained by LEAMES at its current status include an orbital lifetime analysis of the Mars orbiters and the computation of a lifetime map. The map is presented in Fig. 7. The chosen area-to-mass ratio is 0.001 m^2/kg. In Fig. 8 the same orbit configurations are plotted concerning their level of compliance to the 50 year-rule provided by the Principle of Planetary Protection for a set of area-to-mass ratios between 0.001-0.5 m^2/kg. Pericentre and apocenter height are limited to 400 km for a more detailed visualization of the compliance levels. It can be seen that orbiters reach compliance at orbit heights from 225 km and higher. The upcoming investigation includes the analysis of different disposal requirements in terms of orbital lifetimes and their effect on the level of compliance of different orbits and orbiters. The disposal requirements will also be included in the environmental evolution analysis to examine orbital conjunction.

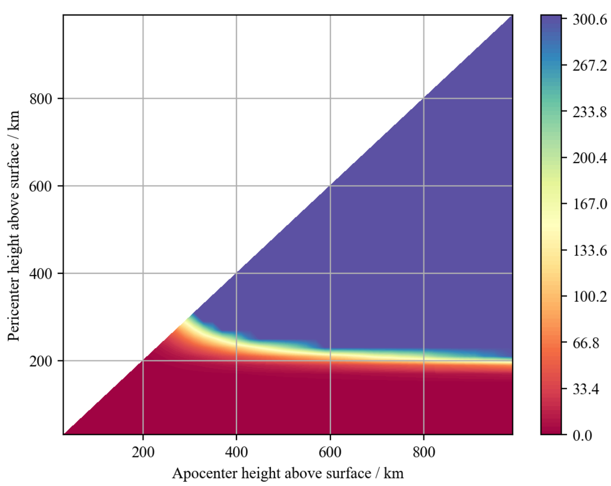

Fig. 8. Lifetime map for an area-to-mass ratio of 0.001 m²/kg.

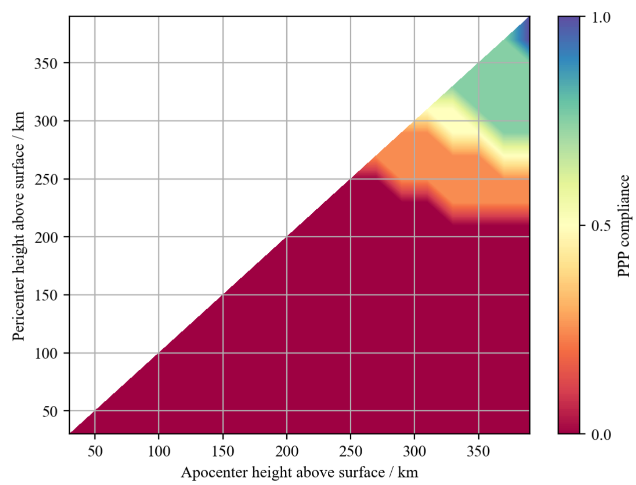

Fig. 7. Planetary Compliance Level for area-to-mass ratios between 0.001-0.5 m²/kg.

6 CONCLUSION AND OUTLOOK

A first framework for the issue of space debris in Martian environment has been developed. Preliminary results include a lifetime map up to 1000 km altitude, which enables the analysis of the level of compliance to the Planetary Protection Principle requirements. A Launch Traffic model was developed to investigate the future evolution of objects in the Martian environment. In order to analyse the potential influence of fragmentation events, the NASA break-up model was also implemented. The regulatory framework concerning potential lifetime restrictions and disposal strategies need to be discussed. The need to establish a set of rules for Mars debris handling will be investigated in the further work of the Master's thesis which is the basis for this paper. In order to examine that, the implementation of LEAMES and the evolution analysis will be finished, and the adaption of a collision probability analysis included. The possibility of collision of two orbiters has been evaluated for the aerobraking phase of the Mars Reconnaissance Orbiter [43]. However, the analysis of close approach and collision avoidance (COLA) options has only been made for the active satellites in Mars orbit. During the aerobraking phase several COLA issues were predicted to occur, so COLA manoeuvres had to be planned. In LEAMES a general investigation of the collision probability for both active and inactive spacecrafts will be implemented, adapted to suite the long-term evolution analysis. So far, approach ideas have been identified. The proper implementation of these and its evaluation is part of following work packages. The satellites are all considered passive. No uncertainties of their positions are considered or known.

- Approach 1: The distance of one point on an orbit towards all other satellite orbits will be evaluated and an accepted distance set as collision criterion.
- Approach 2: Each orbit of an object is transformed into a torus with a tube radius representing a certain close approach threshold. The intersection of the tori will be calculated, and the percentage compared to their non-intersecting volume be considered the basis for collision probability computation. The close approach threshold could be set according to [37], where the radial uncertainty was up to 8 km.
- Approach 3: The orbital environment around Mars is divided in a meshed grid. For each orbit point, the nearest grid points (which in turn represent an approximation threshold) are considered and compared to see if different orbits share identical grid points.

This will lead to initial ideas about what the orbital situation of Mars will look like in 80-100 years. The analysis of the moons as perturbing third bodies will be part of future work.

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