Space Debris Identification, Classification and Aggregation with Optimized Satellite Swarms

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Need

Space debris pose growing threat to LEO and MEO space infrastructure and operations due to the large uncertainty of their population, trajectories, mass, size and etc. Any collision event with a several-millimeter-sized object traveling at orbital speed may cause irreversible damage and further avalanche multiplication of debris. The known number of space debris has increased substantially over the last decades and it is expected to grow further at a nearly exponential rate due to the increased human activities in space in the 21st century. At the same time, efficient methods have not yet been developed for real-time detection and complete characterization of space debris with good accuracy as well as for their deorbiting. The large spread in space debris sizes and trajectories makes their collection and removal a very challenging task, which requires complimentary activities such as accurate detection and classification, threat analysis for LEO objects, prediction of debris orbits evolution and, finally, debris removal at low cost, in a large volume of space and in short response time.

Mission Objectives

Our mission aims at implementing a complete approach for reducing the risks from space debris in LEO by addressing all the required steps – starting from debris detection, through their classification and analysis and, finally, their aggregation in appropriate orbits. We have identified the following objectives 1-5 bellow, listed in their desired order of achievement. Each of them is equally important for mission success.

1. Detection and surveillance of LEO debris larger than 1cm in diameter in the most contaminated Earth orbits in the range of 500km -1500km using small satellites with appropriate payloads for space debris detection. Such payloads can be optimized LIDAR system(s), telescopes and/or multispectral cameras.

2. Establishment, population and maintenance of an accurate database on the ground allowing for real time space debris classification, analysis and modeling of their long term behavior. Such a database should be able to handle a few million records (Big Data) and rely on data both from our small satellite sensors and also processed from existing EO satellites or ground space surveillance systems. Space debris are to be classified based on their orbital parameters, size, mass, spin, albedo and spectral characteristics allowing to determine the debris material type. Such a database would be the backbone of an information system allowing for both estimation of space debris threat and planning of dedicated satellite missions for their removal.

3. Quick implementation of dedicated space debris removal missions by using novel, efficient and short response time (a few days) small satellite launch systems, such as air launch. Such systems would provide the capability to execute small satellite launches from nearly any location on Earth, to any necessary orbit.

4. Aggregation of space debris from a preliminary chosen sector of LEO space to a lower Earth orbit using an intelligent swarm of 5 small satellites launched together as a single unit of total mass ~ 50kg, which deploys an optimized net for space debris gathering, and has a dedicated orbit profile.

5. Provision of possibilities for subsequent removal of aggregated space debris by slowing down their orbital speed or their collection by a dedicated LEO space mission.

Concept of Operations and Mission Elements Description

Space segment: To achieve the above objectives, two complimentary types of sub-missions are to be implemented using two different small satellite designs. We define them as *'Observer'* and *'Aggregator'* correspondingly. The *Observer* sub-mission, which could be defined as a long term mission (3-5 years of operation), is meant to achieve the above Objective #1 a. In it, a dedicated small satellite caring a space debris sensor payload – e.g. a LIDAR system as the one in [1], or an optical telescope described in [2], or a new multispectral sensor allowing for determination of debris material, is deployed in a dedicated LEO suitable for space debris detection. According to ESA and NASA studies shown in Fig1(a,b) bellow, the space debris population in LEO is not uniform. This requires careful orbit planning for the *Observer* in order to ensure space debris detection. For the example of a LIDAR sensor with detection range of ~400km, Fig.2

illustrates the possible *Observer* circular orbit- altitude is in the range ~1200km with inclination ~82-85deg (see the circled area in Fig.1a), allowing for the *Observer* to operate in a less contaminated orbital space and still detect debris in the most polluted orbits around ~800km and ~1500km, located up and bellow its own orbital altitude. The high inclination orbit of the Observer is also optimal for detecting space debris with orbits congested in the polar regions of Earth. The *Observer* sensor(s) have a line of observation up and down alongside the normal to Earth. The *Observer* transmits high volume data from its sensors (e.g. video recording from the optical sensor) to the ground station using a high-speed data link as described in [3],for post-processing and extracting of space-debris related information. The sensor data communication module in the *Observer* is designed as a stand-alone payload module, thus the high-volume of data from the sensor is not overloading the satellite platform's on-board data handling sub-system. To ensure a more efficient achievement of the above Objective #1, it could be planned that several such *Observer* missions are implemented in parallel, varying for each of them the types of their individual sensor payloads (LIDAR, Telescope or multispectral camera), and/or varying the different *Observer* satellites orbital parameters – e.g. inclination and altitude (see the other 'free space' sectors in Fig.1a). All this would make possible to achieve a more comprehensive determination of the LEO debris properties in a shorter period of time.

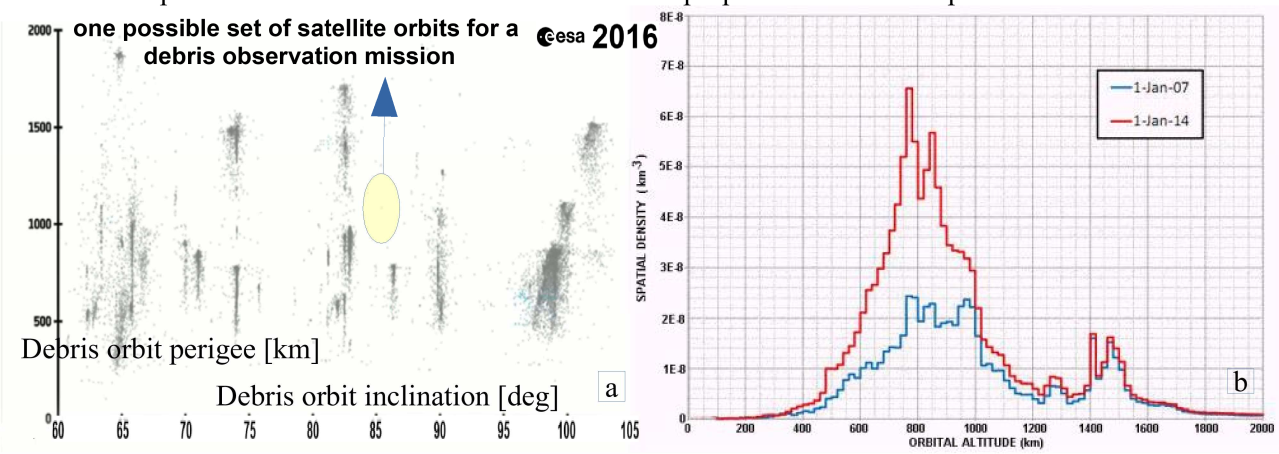
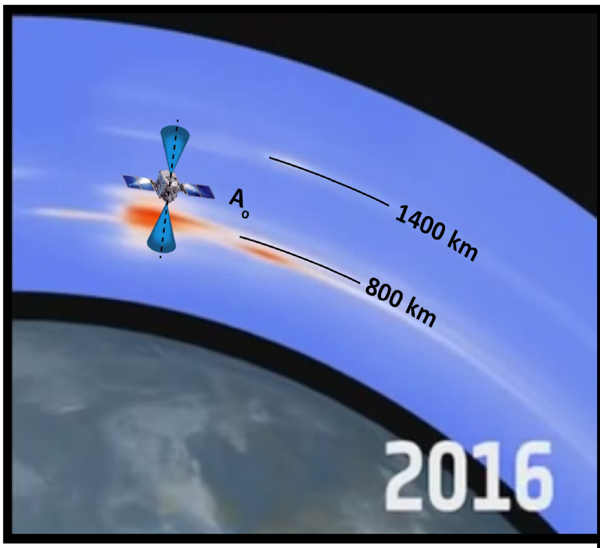


Fig 1: Space debris distribution- (a) ESA, (b)NASA Orbital Debris Program Office (ODPO)



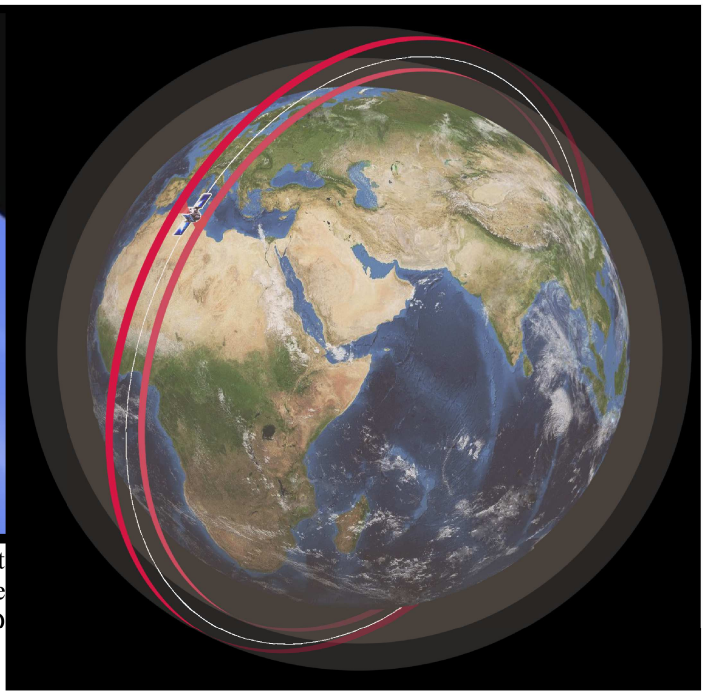


Fig 2: (a) Illustration of the observer's mission orbit position located between the 'belts' of most dense space debris (ref.Fig1b), (b) Illustration of the sensor 3D track coverage in space during one orbit cycle

The *Aggregator* sub-mission is a short term mission (between a few days to a few months duration) meant to achieve the above Objective #4. For this mission, a specialized modular satellite is developed, which consists of 5 autonomous units launched together as a single unit of total mass ~35kg (without the payload).The payload of the mission is a specially designed net, made of lightweight high-strength fibers such as e.g. the well-known Kevlar or novel materials such as graphene stripes, nanofibers and

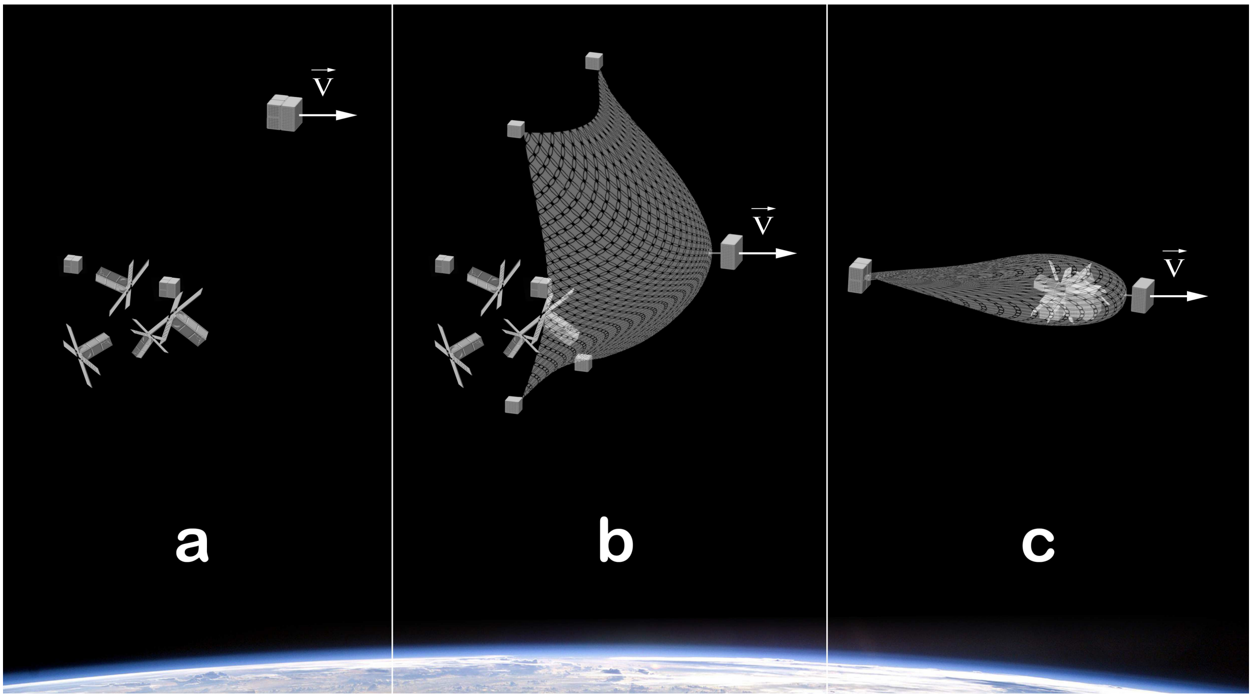


Fig 3 Qualitative illustration of the different phases of aggregating space debris using intelligent satellite swarms. The scale, position and shapes of the objects shown is for illustrative purposes only.

nanocomposites based on proteins, organized in a fractal structure. A specially optimized structural design of the net is implemented to achieve best possible strength/mass ratio. An exemplary design would aim at producing a net of up to 15kg mass, area of ~3km^2 and having unit cell size ~10cm. The fractal structure of the net would allow for production of any other nets of different total area and dedicated unit cell sizes without major re-design. The single unit modular satellite is launched into a target orbit dedicated to aggregate debris from a pre-defined sector of the near Earth LEO space. The *Aggregator* flight profile could be explained as follows:1)Based on data about the trajectories of the target for removal space debris flux, the 5 unit *Aggregator* is launched into an orbit of higher altitude than the target space debris flux to be captured. (the latter could also be e.g. a single piece of a larger derbies or a 'cloud of debris traveling with approximate the same orbital parameters, etc.). The *Aggregator's* orbit inclination and velocity vector is approximately the same as the average values of the ones of the target debris, thus a relative low relative speed between the *Aggregator* and the derbies is achieved- see Fig. 3a. (It is worth to note that for every 1km difference in orbit altitudes, there is about 2km/h difference in the linear velocities between the objects, and the objects at lower orbits have higher linear speeds). 2) The 5-unit satellite is separated into 1 autonomous unit in front and 4 autonomous units in the back, forming a 'swarm'[4] and deploying the net payload in its operational configuration, as illustrated in Fig.3b. For example, a target operational configuration is to achieve e.g. 1km^2 capture cross-section of the net, requiring ~1km separation of the units. Each of the 5 units is to have its own propulsion and AODCS systems, enabling the 'swarm' to dynamically keep its operational configuration -for example, the units at higher altitude will tend to lag behind the units at lower altitude, thus specific dynamic orbit correction shall be implemented to keep the formation as a whole. Self-control and coordination of the units ('intelligent swarm') shall be implemented as described in [4] . This 5-unit configuration will allow for achievement of good control of the net and the center of mass for the entire formation 3) The 5-unit formation with deployed net is to start gradual reduction of its orbit altitude, thus intersecting the orbit of the debris, aimed for interception, and maintaining at the same time low relative speed between the *Aggregator* and the debris. 4) Later, space debris fragments are to be captured by the net during the formation maneuver. It is interesting to note that derbies are expected to 'fill' the net from behind due to their higher speeds. The mass of captured debris (in the case of a debris 'cloud' or stream) would depend on the time of having the net exposed to the debris flux and the density of debris in the area of operation. The captured mass is to be substantially increased when the *Aggregator* swarm is brought to an orbit in the vicinity of large concentration of debris. When a target volume of debris is collected by the net, the 4 units of the swarm fleet are to close the net by an orbital maneuver to avoid debris spread, as illustrated in Fig.3c. Thus, the *Aggregator's* mission is to be generally completed. A more detailed analysis and simulation of the different flight stages is to be presented in the full paper 6) The 'packaged' debris shown in Fig3c could either stay in orbit for a subsequent collection, or be brought to a lower orbit allowing for their burning in Earth's atmosphere. In case of using a conductive net (e.g.based on graphene), another possibility is to rely on the torsion effect of the Lorentz force caused by the conductive net interaction with Earth's magnetic field. This would further slow down the debris package and possibly cause its dive into Earth's atmosphere. All these would allow to achieve our above Objective #5.

Ground segment: The ground segment consists of satellite command and control units (for both the *Observer* and the *Aggregator*), for high – volume data reception from the *Observer* (s) sensors, and of units

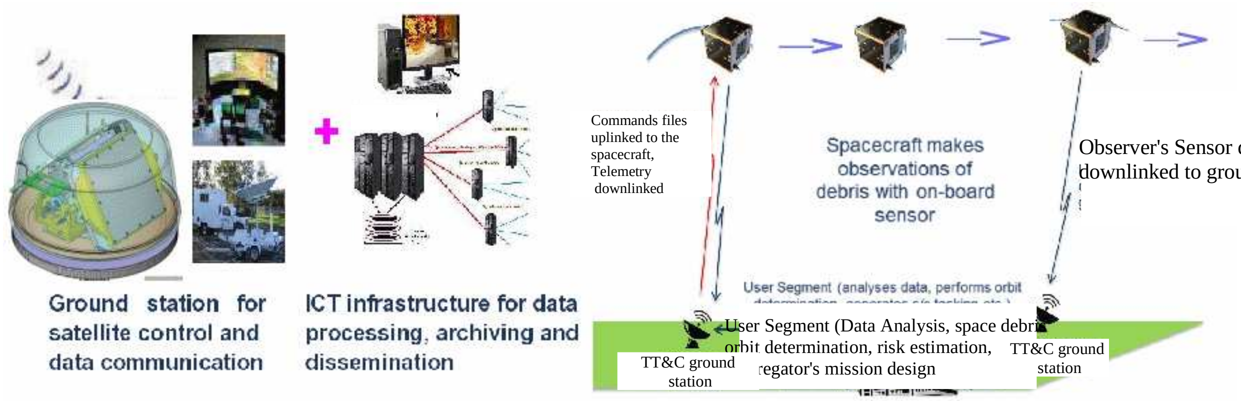


Fig 4 Ground segment top-level architecture and principal operation. It consists of novel compact high-speed antenna for radio communication with the satellites (TTC and data) and of ICT infrastructure for space debris data manipulation

-part of an ICT infrastructure for space debris database management, trajectory analysis, modeling and simulation (the so-called 'user segment'). The radio-communication part of the ground segment is to be build on the basis of using novel compact low-profile VSAT antenna terminals operating in the X-band [3].

It is important to mention that the user-segment part of the ground segment is to be responsible for providing mission planning information of the *Aggregator's* satellites. This information is to be provided both from the analysis and modeling of space debris data from the *Observer's* missions but also from dedicated analysts of data from other existing space debris sensor on Earth. A novel approach would also involve processing of existing imagery or radar data from the Earth observation and meteorological satellites in LEO/MEO, which may contain information about space debris located in lower orbits. The *Aggregator's* missions are planned based on the following example considerations: density of space debris, if the target is a cloud of debris or a single bigger object; if the target debris are traveling at similar speeds and directions; speed of self-rotation of debris (e.g. debris larger than 15cm should not rotate at a speed higher that 2 rotations per second; possibility to achieve low relative speed between the *Aggregator* and the cloud of debris in order to minimize the risk from collision for the *Aggregator's* units. The ground segment will continuously process the received data, thus ensure a continuous improvement of the accuracy of information about the space debris trajectories, population, etc. Semantics-based approach for data extraction and manipulation from distributed sources is to be used thus allowing to efficiently handle a few million records.

Launch: We propose to use a system of air-launch for implementing *Aggregator's* and *Observer's* sub-missions. This is motivated by several objectives such as: achievement of low cost for launch and quick response for implementation of *Aggregator's* mission with different mission parameters defined by the orbit properties of the targeted for aggregation space debris. Air launch makes possible to use almost any geographic location for satellite launch and achieve the most optimal orbit altitude and inclination for the particular mission. At present, there are several promising developments of air-launch systems using a high-speed jet fighter which launches a dedicated rocket satellite carrier at altitudes above 10km reaching orbits ~1000km.

Fig 5:(a)Microspace-2 project (Russia)-40kg payload to 1000km orbit,(b)ALASA project (USA)-45kg payload, (c) GOLauncher 2(USA)-45kg payload using a modified LearJet35,possible orbits ~1000km, inclination 0-98.7 deg

Key Performance Parameters

Our approach to space debris risk mitigation depends on: development of reliable sensors for in-orbit space debris observation and quantitative trajectory analysis. Sensor technical capabilities are crucially important. The LIDARs should allow for detection of objects larger than 1cm from a distance of at least 400km, provide a field of view-FOV (with or without scan) of at least 20deg and operate at frequencies suitable for space debris material. The optical sensor should have largest possible FOV to make possible efficient observation of debris trajectory evolution. For debris Aggregation, a key element is the design of the flight maneuver allowing for deployment of the net and its exposure to the debris flux, while keeping the formation of the 5 autonomous units at a distance of the size of the net. The propulsion system of the units is based on hot-gas thrusters (ethyl alchohol) providing ΔV of 300 m/s, thrust of 0.3N and a specific impulse of 800 m/s.The lightweight net used to gather the debris should be able to sustain impacts with debris of pred-defined energy to mass ratios (debris impact with ratios of ~40 J/g are typically considered catastrophic). Other mission specific parameters are given in the sections above, and are to be further discussed in the full text.

Implementation Plan

The approach proposed here for addressing the space debris problem in LEO requires development of several complex components which, as such, could only be implemented by a strong and motivated team of international experts and organizations. Strong inter-government support is needed also due to possibly existing legal issues for implementing air-launch and a space debris removal mission. Provided there are no financial or legal constraints, we foresee a 4 year period for implementing the first Observer's and *Aggregator's* missions. We plan to divide the activities in four major work packages as illustrated on the top level view in Fig.6. WP1 will deal with the design of the *Observer* and *Aggregator* platforms. In the first year, detailed feasibility studies will be executed to identify all needed technological and engineering requirements. In the end of the fourth year, first air launches are to be done. WP2 is to address the implementation of the ground segment hardware infrastructure. In WP3 the required software tools for analysis of the space debris data and large database manipulation are to be developed. WP4 will deal with detailed education and training of the involved experts and executing background R&D needed for implementing the entire mission.

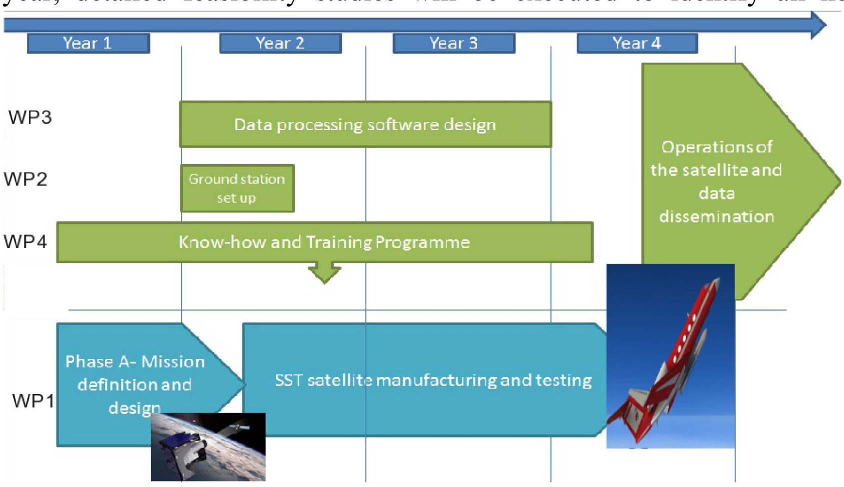


Fig 6 Top Overview of the mission implementation schedule

The following mission risks could be outlined (not in order of priority):low efficiency of debris detection by in-orbit sensors and difficulties in determining space debris trajectory parameters with sufficient accuracy; complex mission design for the *Aggregators* flight including execution of necessary orbital maneuvers by individual units; complex implementation of the 5-unit satellite swarm structure; debris impact with the *Aggregator's* elements; complex and risky deployment and un-deployment of the net; risk of net destruction and of unpredictable behavior of the system of space debris captured by the net and the *Aggregator,* etc.

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