A Complete SSA Scheme for a Sustainable Low Earth Orbit: Space DATA Aggregation and AI Combined with In Orbit Inspection

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ABSTRACT

The exponential increase in the number of satellites along with the hazards of the space environment they encounter endangers the sustainability of low earth orbit (LEO). The consequences of events such as collisions, fragmentations and fatal failures are then becoming more than ever a threat to any kind of space activity. Therefore, the space situational awareness is of utter importance in all its aspects, i.e., assessing and predicting the risks from space weather and SST (Space Surveillance and Tracking), in addition to implementing mitigation measures. In this context, this paper covers the benefits of in-orbit inspection combined with the aggregation and processing of existing space data, proposed by the French company SpaceAble for low earth orbit sustainability. Collision risk awareness for a LEO constellation is raised in this paper through the analysis of the conjunction risks of the Starlink constellation. An inspection plan is also derived in terms of the number of inspections for different scenarios, and with respect to different LEO altitudes.

1. INTRODUCTION

The space industry is witnessing today an exponential growth in terms of number of satellites, which is due to the various recent and future constellation projects in the low earth orbit (LEO). According to the UCS (Union of Concerned Scientists) satellite database [1], there are more than 4000 active satellites in orbit as of April 2021, with a number of deployed satellites that increased with 120% in 2020, compared to 2019 [2].

These satellites are facing the harsh and hostile space environment. Materials and electronics are becoming even more vulnerable with the advent of the New Space. Temporary or permanent damage to an equipment or to the whole system may be incurred, which can provoke hazardous events. Consequences can be explosions, partial loss, or a premature ending of a satellite's life [3] before performing an atmospheric reentry (low-altitude satellites) or reaching a graveyard orbit (high-altitude satellites). This, combined with the large number of space objects, highly contributes to the increase of collision risks, which participates in the proliferation of orbital debris and the establishment of the Kessler syndrome. Therefore, the Space Situational Awareness (SSA) becomes of utter importance. The SSA program of the European Space Agency (ESA) [4] covers the detection, prediction and assessment of hazards related to both Space Weather (SWE) and space traffic through Space Surveillance and Tracking (SST), in addition to Near-Earth Orbit (NEO) natural objects. SSA is not only about hazard alerts and real time decision making, it is also seen as an opportunity to mitigate and reduce the risks threatening the low earth orbit sustainability.

Monitoring SWE and SST is considered as a way to reduce anomalies and collision risk, which in turn should mitigate the creation of orbital debris and sustain the resilience of future generations of satellites. In addition, monitoring satellites through routine check-ups to detect anomalies and observe any kind of deterioration is important to prevent life-ending failures. In this context, SpaceAble, a French company working on SSA, proposes two complementary systems: a platform meant to aggregate critical space data regarding SWE and SST, and an inspection satellite. The goal is to enhance anomaly diagnosis for a longer lifetime of satellites in orbit, mitigate sudden and premature ending of satellites' missions, help preparing active debris removal missions, and enhance current SSA capabilities. Such a service is intended to contribute to the enrichment of available space data for different space actors and participate in the sustainability effort of the low earth orbit.

In the remainder of this paper, a brief overview of the SWE sources of hazards, and mechanisms on satellites will be presented in Section 2. An analysis of the evolution of catalogued satellite anomalies according to SERADATA database is provided in Section 3. Then, an analysis of the collision risk encountered by the Starlink constellation is provided in Section 3. Finally, the SSA approach proposed by SpaceAble is detailed in Section 4.

2. SPACE WEATHER FACTORS

This section briefly describes the space weather sources of hazards, and the induced mechanisms affecting the health of on-orbit spacecrafts. The most part of anomalies that affect satellites are due to the space weather. It is therefore important to understand each phenomenon and its effect on satellites in order to develop mitigation measures, whether it is in terms of material and electronics or in terms of recommended behaviors.

The SWE sources of hazards that are related to the solar activity are responsible of triggering a large part of spacecraft anomalies ([5] [6]).The constant stream of the solar wind along with the solar events that are correlated with the 11-year solar cycles such as the coronal mass ejections (CMEs) and solar flares are the main components of the solar activity. Their interaction with the Earth's magnetic field creates what is collectively referred to as "geomagnetic activity". A geomagnetic storm occurs when there is an injection of high-energy plasma into the Earth's magnetosphere with an intensified magnetic field strength. The main phase of a geomagnetic storm, during which satellite anomalies would be expected to occur, typically lasts between two and eight hours. The consequences of the solar activity can be summarized below:

- Concentrated highly charged particles that are trapped in the Van Allen inner and outer belts within the magnetosphere. These energetic particles come from indeed the sun (Solar Energetic Particles SEP) but also from the galactic cosmic rays (GCRs) and they can be a threat to satellites in high LEO, MEO and GEO orbits. Although LEO satellites might experience less impact from the radiation belts, they incur great threats if their orbits pass near the polar regions (high inclinations) or through the South Atlantic Anomaly (SAA).
- Interaction with the thermosphere: in low LEO the upper atmosphere still contains elements like oxygen, dinitrogen, dioxygen and helium. A higher solar activity induces a higher atmospheric density that reaches higher altitudes due to the heat up of the thermosphere. This affects the orbital lifetime of satellites, as explained further.

The SWE mechanisms triggered by the above sources ([7]) are summarized as follow:

- Spacecraft charging: it is mainly described as the accumulation of charge either at the surface of the spacecraft (surface charging) or within the spacecraft itself (internal charging). Being responsible of more than 50% of known anomalies [8] the main consequence is electrostatic discharge which can bias instrument reading and cause physical damage to equipment and nearby circuitry.
- Single events effects: it happens when a single energetic particle hits a sensitive component. Consequences can go from a simple bitflip in a memory cell to a complete destruction of a device or a system.
- Total ionizing dose: it is a long term mechanism resulting from the persistent absorption of energy by the spacecraft, quantified in rads (Radiation absorbed Dose), and ionization. It actually depends on the orbit altitude, orientation, and time of exposure. It leads to gradual degradations of electronics' performance and solar panels efficiency.
- Displacement damage: It is due to cumulative long-term non-ionizing dose and resulting in nuclear interactions, typically scattering, which causes lattice defects and damages semiconductors and materials.
- Atmospheric drag: the density of the atmosphere provokes decay of satellites' orbits in LEO where the orbital speed is higher and so is the density of the atmosphere. The latter phenomenon induces a stronger drag and increased heat which results in decay and the same process happens again. This requires satellites to perform orbit correction maneuvers, especially in low altitudes, which leads to a shortage of propellant while the number of collision avoidance maneuvers is increasing.
- Surface erosion: this is the process of changing the properties of spacecraft's surface materials due to oxidation caused by the orbital environment including atomic oxygen in thermosphere (up to 650 km). This can have a significant impact on the thermal properties of satellites (degradation of the Multi-Layer Insulation MLI), but also on the electrical properties in addition to the degradation of payloads' performance such as the clouding of optical instruments or degradation of antenna diagrams.

Understanding these mechanisms and potentially predicting SWE events that would intensify any of them is crucial. Moreover, understanding the effects they have on satellites and the consequent anomalous behaviors they provoke on the different subsystems and payload is important for risk management and mitigation at different levels. In the next section, we analyze anomaly occurrence according to the SERADATA database.

3. ANALYSIS OF SPACECRAFT ANOMALIES

Soft and Hard errors affecting the health of spacecrafts are provoked by the different space weather mechanisms mentioned in the previous section and MMOD (Micrometeoroids and Orbital Debris) in addition to other factors related to non-space environment events. The latter concern software and hardware manufacturing and design errors, operator errors and technological actions (accidental or malicious).

On the one hand, a spacecraft anomaly is defined as a "mission-degrading or mission-terminating event affecting on-orbit operational spacecraft" according to the National Research Council (NRC, 2011). On the other hand, Anomalies can be classified from a signal point of view into two categories [9]:

- Univariate anomalies, concerning a single parameter
  - Point anomalies in the form of an outliers
  - Contextual anomalies for an existent value that is normal in another context
  - Collective anomalies for a nonexistent sequence of instances for an instance that exists
- Multivariate anomalies, concerning a change in the relation between correlated parameters

The various anomalies and failures that have been reported by operators can be distinguished by their effects on satellites: device part failures and burnouts, degradation (optical components, electronics, solar cells, thermal properties…etc), data corruption, biasing of instrument readings, system shutdown, phantom commands … etc.

From an operational perspective, SpaceTrak of SERADATA classifies these anomalies according to both their severity and the affected subsystems.

The severity level of anomalies distinguishes four classes: (i) Class I that includes all serious anomalies that are defined as catastrophic failures that led to the retirement of the spacecraft, (ii) Class II that includes all serious anomalies that encompasses all major failures. These affect the operation of a satellite or its subsystems on a permanent basis, unless there is repair, (iii) Class III-LR that includes all major non-repairable failures that cause the loss of redundancy to the operation of a satellite or its subsystems on a permanent basis, and finally (iv) Class IV that includes all minor /temporary/repairable failures that do not have a significant permanent impact on the operation of the satellite or its subsystems.

Fig. 1Fig. represents the number of anomalies of each class over each period of the solar cycles (solar maximum and solar minimum) until April 2021, normalized per year and per satellite. It can be noticed on the past twenty years that the most likely anomalies to happen are of class II (leading to major failures). These have been decreasing from one chance in 28 during the solar minimum of cycle 23 (2001-2008) to one chance over 155 during the solar maximum of cycle 24 (2008-2014). However catastrophic anomalies of class I seem to be more or less stabilized over the past few periods, despite the decreasing intensity of previous solar cycles compared to cycles 21 and 22. Hence having a probability of catastrophic failures of Class I equal to 5×10^{-3} during the ongoing cycle 25 (computed over 16 months) is alarming compared to a probability of 7×10^{-3} during the past solar period (computed over 5 years). This means that there are other factors affecting the probability of failures apart from the number of sunspots and satellites.

The anomalies regarding the affected subsystems concern: attitude control; beam and antennas; control processor; mechanisms, structures and thermal; Payload instrument; Power, including the battery, the electrical distribution system and the solar arrays; Telemetry, Tracking and Command; Transponder; Unknown; and Retired satellites due to any of the above categories of anomalies.

Fig. 2 represent the distribution of the number of anomalies, normalized per year over each solar cycle and per satellite, according to the impacted subsystems. It can be observed that major issues leading to the retirement of satellites are particularly dominant for the past ten years. Otherwise, payload, attitude control and power related anomalies are the most recurrent, followed by TTC (Telemetry, Tracking and command).

We recall that anomalies can be caused by many sources including space weather which is mainly related to the solar cycle. However, the number of anomalies during a solar cycle compared with another cycle can also depend on other factors such as the number of debris, the human technological actions, the design, the used materials and the used orbits. Besides, a lack of information regarding catalogued anomalies is suspected to be considerable, especially for LEO satellites [10] [11] [12]. As a matter of fact, most satellite operators tend to keep anomaly databases of their own satellites private, which means that the format of these databases are different from one operator to another. Moreover, detailed data for defense and commercial satellites are not typically shared, whether publicly nor among organizations.

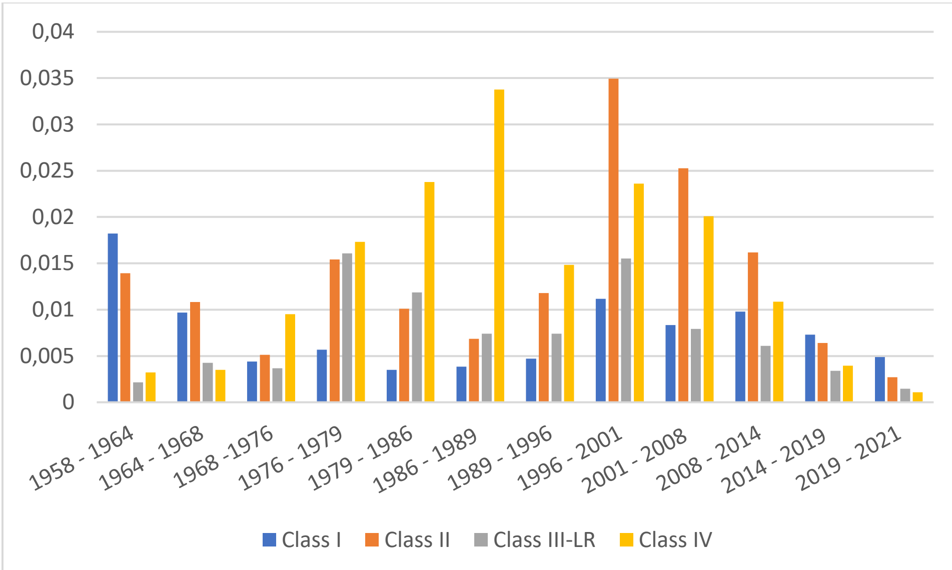

Fig. 1. Anomaly categories over time normalized per year and per satellite

The catalogued anomalies in SERADATA (see Fig. 3) show that satellite retirements due to anomalies (mission termination) are indeed the most recurring during the last ten years, followed by unknown, attitude control and payload instrument anomalies. The unknown anomalies contributing to the sixth of the total anomalies during the past ten years is alarming and threatening to the sustainability of the LEO orbit. Better investigations and tools need be put into place in order to clarify the unknown parameters contributing to these anomalies.

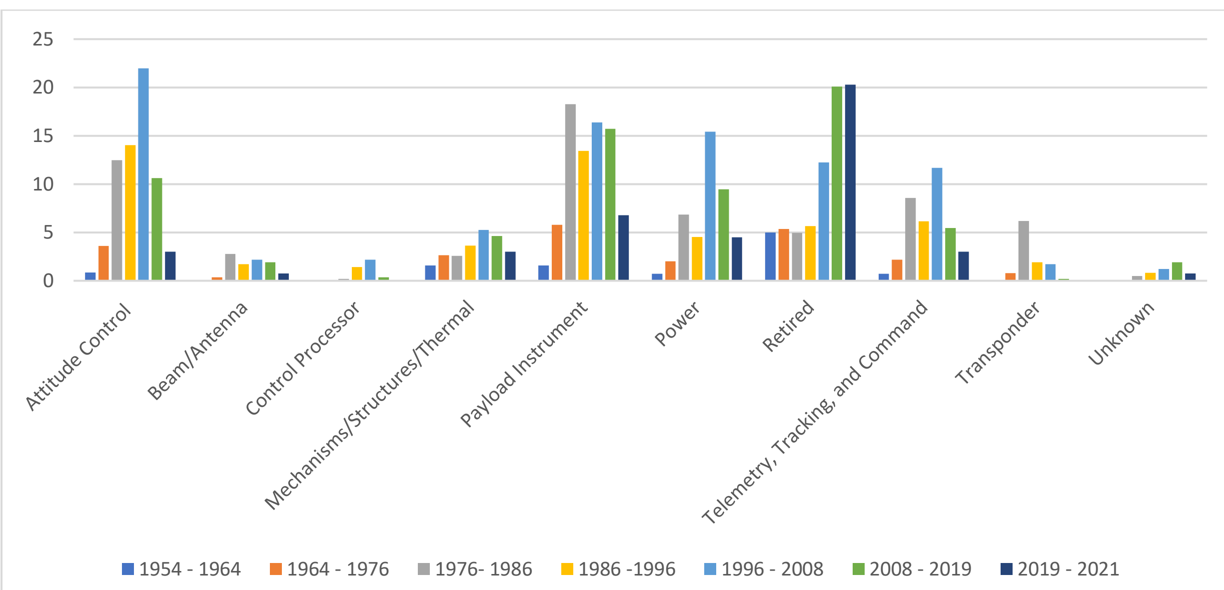

Fig. 2. Impacted subsystems over time

In order to evaluate the content of SERADATA database in an SST (Space Traffic Management) point of view, we have extracted information about reentries, active satellites and retired satellites in LEO orbit with respect to solar periods. Thus, Fig. 4 shows the following information:

1. The total number of satellites that have been active at least once over a time period called the period's active satellites.
2. The number of satellites remaining active at the end of the period, called the period's remaining active satellites.
3. The difference between the period's active satellites and the number satellites that incurred a reentry or a retirement during the same period. The latter is called the period's dead satellites.
4. The difference between the third information and the second information, called the missing information.

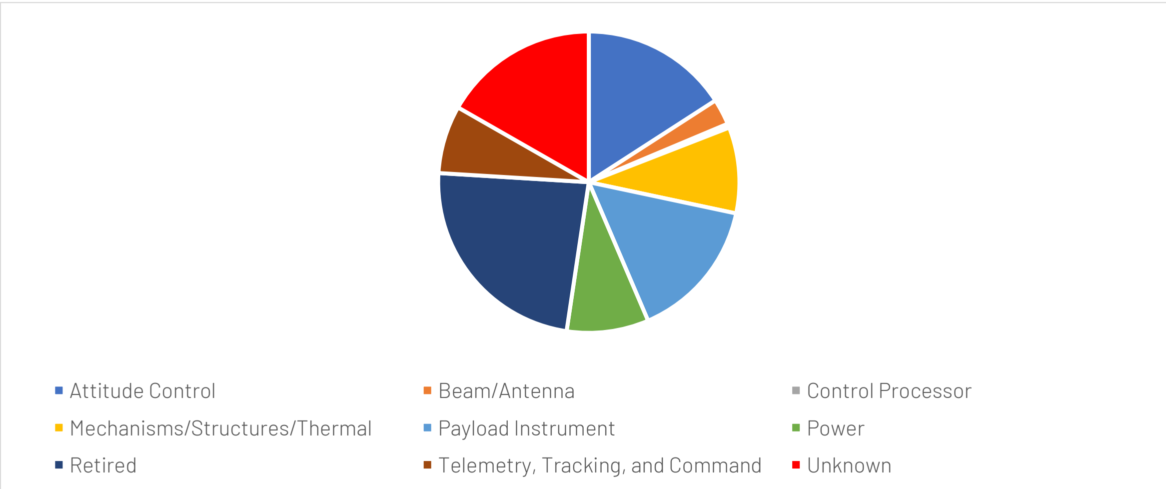

Fig. 3. LEO anomalies since 2010

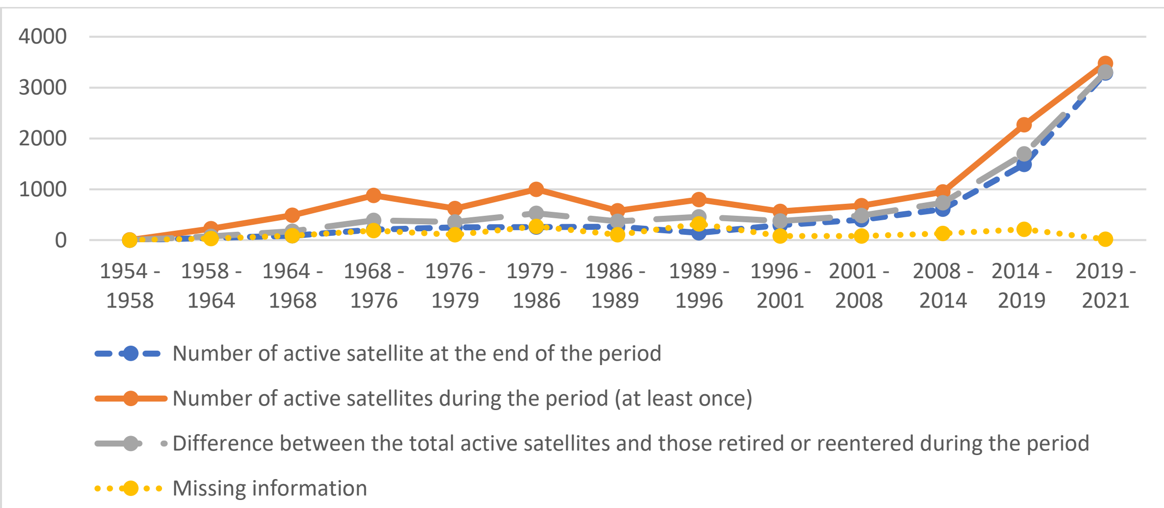

Fig.4. Active and non-active LEO satellites over time

On the one hand, we can observe on Fig. 4 that the number of remaining active satellites of a given solar period is much lower than the period's active satellites. This means that the number of retired and reentered satellites is not negligeable given their short lifetime in LEO orbit. In this case, the cycle's remaining active satellites should be equal to the difference between the cycle's active satellites and the cycle's dead satellites. However, it can be observed on the same figure (Fig. 4) that this not the case, which means that there is a considerable lack of information that operators might omit to share publicly. In the last period between April 1st, 2014, and December 1st, 2019, the missing data is about 200 non reported events, which is not negligeable. As for the past 10 years space surveillance systems using RADAR and optical observations have been able to observe and list all atmospheric reentries, it is most likely that the missing information concern catastrophic anomalies leading to satellite retirements.

With the advent of mega constellations, satellite failures are a fact threatening the sustainability of earth orbit. By 2017, a failure rate of 21% had hit the first generation of Iridium satellites, i.e., 20 satellites out of 95 had failed. Among which 15 were tumbling and no longer controllable [13]. This gives an idea on the consequences that these mega LEO constellations can have if no SSA and debris mitigation solutions are considered. Moreover, anomalies should be monitored, identified and traced back to the source in order to mitigate life ending failures.

Satellite monitoring is performed through the analysis of telemetry data both onboard in real time and later on the ground. It is to be noted that thousands of parameter measurements constitute the telemetry data, generally gathered through onboard sensors. On the one hand, some failures are handled by the implementation of FDIR on the onboard software. On the other hand, a finer monitoring is performed on the ground for anomaly detection and prevention. However, in both cases the main anomaly detection technique that is applied today is threshold-based and is very limited [14]. As a matter of fact, this method known as OOL for out-of-limits defines for each continuous parameter an upper and a lower bound within which the behavior is considered normal. An alarm is issued whenever a threshold is exceeded. This means that only certain types of errors can be detected and those lying withing the threshold cannot be perceived. Moreover, tracing some anomalies back to the source when they are detected appears to be extremely difficult without in-orbit inspection. This is why the attribute "Unknown" is associated to a vast majority of orbital anomalies or some of them may be erroneously attributed to a meteoroid or orbital debris events. Therefore, in-orbit inspection is expected to provide insights from on-orbit encounters that adversely affect satellite operations **[5]**.

4. ANALYSIS OF STARLINK COLLISION RISK

The Low Earth Orbit is generally considered to extend from around 120 km to about 2000 km. Below 120 km, the satellites cannot remain in orbit while above 2000 km, the intensity of radiation is too high for the satellites to operate properly. Most of space debris resides in LEO. In this region, the amount of space debris varies significantly with the altitude. The greatest concentration of debris is found near 750-1000 km where the two worst fragmentation events occurred: (i) the intentional destruction of the Fengyun-1C weather satellite by China in 2007, and (ii) the accidental collision between the American communication satellite, Iridium-33, and the retired Russian spacecraft, Cosmos-2251, in 2009 [15]. Both events have significantly increased the number of large space debris in LEO (see Fig. 5) that now represent one-third of all cataloged space debris. It is therefore an aspect to be considered by the mega constellations that are being deployed in this orbit.

Starlink is a satellite constellation project operated by the company SpaceX. The goal is to develop a low-cost, high-performance satellite bus to implement a new Internet communication system. This constellation is currently the most advanced project by the number of active spacecrafts, with 55% of the active satellites in Space being Starlinks as of the 1st of June 2021. Starlink is already partially operational. As of June 2021, more than 1,735 Starlink satellites have been launched, of which 1,659 are still in orbit. Each launch deploys 60 satellites. Many plans are emerging for similar large constellations of satellites and they will all have an important influence on the evolution of the space debris environment and consequent impact on the population of man-made satellites orbiting the Earth. Starlink being not fully deployed and some Starlink satellites having re-entered because of anomalies detected right after their launch or after a short stay in orbit [16], the current architecture of the constellation is not uniformly spread around the world so far. This situation shows the importance to have a collision risk study for the provisory architecture of the constellation as the relative motion between the satellites will evolve with it and thus its probability of collision.

We have calculated the number of conjunctions[1] involving one Starlink satellite over a period of seven days. To identify the conjunction cases where a Starlink appears we have computed the orbital evolution of the cataloged objects evolving in LEO. For this part, we have used the database of the Unites States Space Command which is the U.S. government entity responsible for space domain awareness and space situational awareness. This institution provides at a no-cost basis the data of most of the space objects under the Two-Line Element (TLE) format through the website Space-Track.org. We recall that the TLE set is a data format which contains information that makes it possible to know a space object's orbit around Earth at a specific time. The first line of a TLE is the name of the object which

[1] A conjunction is the closest point of approach between two objects triggering an operator analysis but not necessarily an avoidance maneuver nor implying a collision [21].

relates to the name of the satellite or its launcher. The next two lines are the coding of the object in question, they each have 69 characters, the first line giving general information, and the second the orbital parameters, i.e., parameters allowing to describe the trajectory of an object.

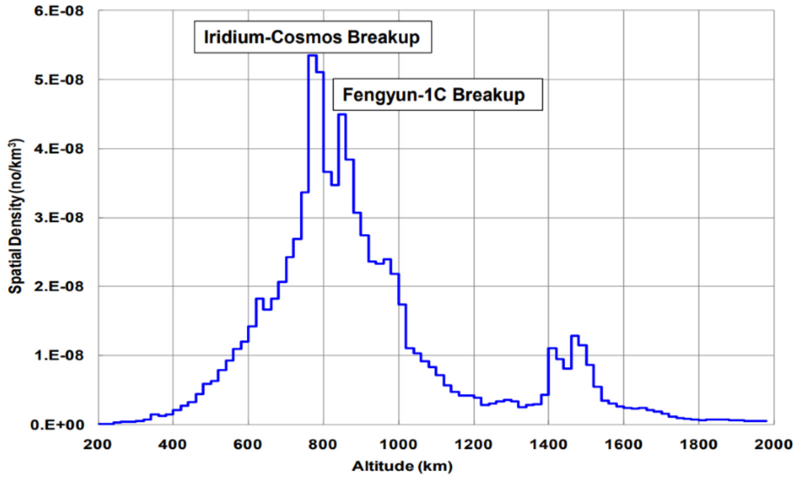

Fig. 5. Space debris in Low Earth Orbit *[15]*.

The probability of collision refers to the probability that the two objects are less than a specified distance apart at their time of closest approach. As the two objects are moving in 3-dimensions, the risk of collision is a dynamic 3D problem. However, it can be reduced to a static 2D dimension problem by calculating the probability of collision in the 2D collision plane [17]. By changing the dimension of the problem, it's assumed that: (i) the duration of the conjunction is short, (ii) the position uncertainty distributions of the objects at conjunction are Gaussian, and (iii) the relative motion is rectilinear in the encounter region.

The probability of a conjunction is performed for no more than 7 days while the result is used for a maximum of three days and updated each day. The results can be thus slightly greater than the reality, but in regard to the uncertainties we have on the rotation, size and trajectory of a space object this method is a good compromise. It is to be noted that this method is currently used by NASA [18] and the US army.

The probability of Collision (PoC) is computed through this formula [17]:

$$PoC = \frac{1}{2\pi|\mathrm{Det}(C)|^{1/2}} \iint_{x^2+y^2\leq d^2} exp\left(-\frac{1}{2}(\boldsymbol{r}-\boldsymbol{r}_{S/P})^T C^{-1}(\boldsymbol{r}-\boldsymbol{r}_{S/P})\right) dxdy$$

With:

- C, the 2×2 projection of the combined 3×3 covariance at the time of closest approach onto the collision plane. To obtain the covariance at conjunction, it is necessary to propagate it from the time it is calculated to the conjunction time.
- $\mathrm{Det}(C)$, the determinant of C.
- d, the sum of the two object sizes.
- $r = (x, y)^T$, any point in the collision plane such that $x2 + y2 \leq d2$.
- $r_{S/P} = (r_{S/P}, 0)^T$, the position of the secondary relative to the primary along the x-axis in the collision plane.

As a result, we have identified 56 888 cases of conjunctions between the 21st and 28th of July. They are distributed as follow:

- 28 848 cases of conjunctions involved at least one Starlink satellite
- 19 310 cases of conjunctions involved 2 Starlink satellites (it is an internal conjunction),
- 5476 cases of conjunctions involved a Starlink satellite and a non-operational object
- 3208 cases of conjunctions involved a Starlink satellite and an operational object
- 454 cases of conjunctions involved a Starlink satellite and an object of which the operational status is unknown.

These results show that the number of conjunction cases per satellite (from the Starlink constellation) is considerable, and is expected to grow with the increase of the population of space objects. This will consequently induce more regular avoidance maneuvers, which decreases the operational lifetime of satellites in terms of propellant. It is therefore imperative to prevent a satellite from becoming uncontrollable and preserve its ability to maneuver.

5. PROPOSED SSA SOLUTION

The probability of occurrence of the different risks and failures is increasing as the number of satellites increases, and particularly collision risks. As mentioned earlier, failures leading to a total shutdown of a satellite or to a loss of its maneuverability is becoming more than ever a danger, threatening the sustainability of the low earth orbit. In other words, one collision with a relatively large debris triggering a chain reaction of collisions might be inevitable in the near future if no space traffic management and surveillance is rigorously applied. There is also an urgent need to increase the reliability of the risk models, assess the state of assets in orbit, and understand the SWE risks and consequences in addition to their prediction.

One way to mitigate catastrophic failures leading to total shutdowns is thus monitoring the SWE in order to assess and predict any upcoming hazardous events. This way, satellites can be put into safe mode for example to minimize the effects of the SWE event. In addition, in orbit inspection assessing the general state of satellites might contribute in the decision making of deorbiting a satellite and refining the root cause investigation regarding anomalies. In this context, SpaceAble offers an SSA scheme for LEO operators and space actors, complementing the current solutions. The SpaceAble solution is an approach based on two complementary systems to provide an SSA service that is efficiently useful for different space actors: a space data platform and an inspection satellite. It is to be noted that this paper focuses more on the inspection part.

5.1. SPACE DATA AGGREGATION AND PREDICTION

First, a platform that aggregates the complete spectrum of Space Situational Awareness (SSA) data, that is both Space Weather (SWE) and Space Traffic Management (STM), in addition to anomaly detection algorithms, is proposed. Covering both SWE and STM is essential to achieve accurate understanding and models of SWE mechanisms, enhance the trajectography of space objects, and assess their environmental and state conditions through novel techniques based on artificial intelligence (AI). The goal is to train AI algorithms for SWE nowcasting and forecasting and thus alert operators in case of approaching hazardous events. It is to be noted that in order to have a precise STM and mitigate the Kessler syndrome, SWE is crucial. As for anomaly detection, we expect the proposed non supervised and semi-supervised learning algorithms in the literature to be insufficient as telemetry data keeps growing in size and heterogeneity. Moreover, identifying the source of an anomaly after it is detected remains challenging especially when it comes to orbital debris or meteoroid events.

Furthermore, current SSA services are facing major issues: lack of data, lack of accuracy and reliability, ununified data, … etc. The data platform ISSAN (International Space Situational Awareness Network) intends then to aggregate and integrate predictive SSA models. An increase of the overall accuracy/reliability of both SST and SWE data is targeted. The goal is to forecast and mitigate risks related to the LEO space environment.

To deal with the most confidential data, a layer of cryptography is added in a way that makes it possible to process data without breaking confidentiality. As ISSAN is intended to be neutral, blockchain technology is used to certify data and guarantee their integrity. ISSAN presents a unique level of comfort in accessing available data for safe and sustainable space operations. This platform is intended for insurers, space operators, manufacturers, launchers in addition to the space research community, with specific features developed to answer their specific needs. ISSAN works as a global marketplace for data providers and data consumers.

It features an intuitive interface and gives access to multiple dashboards updated in real time, which include: centralization and filtering of space data, constellation monitoring and satellite health KPIs, risk simulation of space events, and automated recommendations. These services are based on a tailored mix of technologies: platform, cryptography, blockchain, IA/ ML, and space weather models.

Finally, the use cases of ISSAN according to each actor are: (i) insurers, reinsurers and brokers: ISSAN will help them to assess risk easily to evaluate, in an accurate way, the insurance premiums (e.g. standard health report, risks predictions); (ii) operators, manufacturers and launchers: ISSAN will help them monitor and track accurately their assets and prevent risks in an hostile space environment (e.g. risks predictions, alerts, maneuver simulations); and (ii) the scientific community: ISSAN centralizes, for instance, all data related to Space Weather, allowing the science community to access SpaceAble knowledge in a simple and intuitive way. This tool can also contribute to this knowledge base.

5.2. IN ORBIT INSPECTION

The telemetry data is preprocessed before it is analyzed for anomaly detection. It is important for different space actors to trace back anomalies, once detected, to the source in order to identify what could have caused it. Moreover, validating the risk models on which the design of satellites is based is crucial to optimize their manufacturing, especially for future generations. These two aspects participate in the increase of the lifetime of satellites in addition to the enhancement of the tradeoff between cost and risk.

In this context, the Orbiter, which is an inspection satellite, provides in-situ information for in-orbit diagnosis from observations. It is a small microsatellite operating in LEO and provided with inspection-related payloads. The first generation of the Orbiter will be equipped with a camera in the visible domain, a space weather payload and a RADAR. On the one hand, the camera in the visible domain makes it possible to observe external consequences of anomalies. On the other hand, the RADAR used for navigation is necessary to perform a safe rendezvous with the target satellite. The space weather payload will harvest in situ data that can be processed by the ISSAN platform. For the next generations of the Orbiter, other instruments will be added.

5.2.1. Use cases of the Orbiter

Each of the use cases of the Orbiter will be described next: root cause investigation, model validation and special phenomena detection.

- *Root cause investigation*

Generally, the satellite operators are able to detect anomalies through monitoring data and determine in some cases the causes of anomalies. However, what causes an anomaly or a failure may remain unknown and often many causes are possible for the same anomaly or failure. Identifying the precise cause or narrowing the field of possibilities makes it possible for space actors to better deal with the anomalies, especially for the future generations of satellites. This can lead to review the satellite design in order to robustify an equipment or a subsystem and impose extra qualification and testing for example. In addition, a space weather related cause would enable operators to optimize the safe mode and better plan the spacecraft’s behavior during a predicted space weather event. A misunderstanding of an anomaly cause might hence induce extra cost and schedule overrun. Analyzing monitoring data such as telemetry do not determine the exact cause of an anomaly due to the lack of in-situ observations. However, some causes of anomalies can be perceived, and confirmed using the Orbiter through visual inspection. Some examples of events that can be confirmed through the observations of the Orbiter are listed below.

Space weather events:

- ESD effects on solar panels, resulting from spacecraft charging. They are characterized by a change in the surface aspect, and an electric dysfunction of the solar panel as seen in the Fig.6.

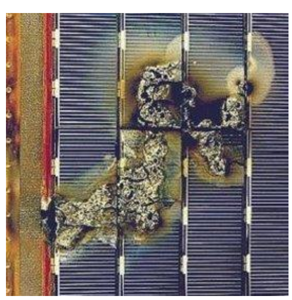

Fig. 6. Impact of ESDs on solar panels *[19]*

- Potential observable erosion on antennas' RADOMS or on the Multi-Layer-Insulation (MLI), that is due to atomic oxygen. It can be detected by a contrast change through appearance of roughness on the structure or by a change of emissivity (IR camera).

Human-related events:

- An insertion error can then provoke collisions between satellites liberated by the same launch vehicle. As the relative velocity is very low, it is more likely to have part failures or minor fragmentations rather than mission-terminating collisions. Inspection right after an orbit insertion makes it possible to observe premature fragmentations or chock impacts on satellite structures. Moreover, early-stage failures are common, which makes the identification of the phase during which the failure occurred important. It makes it possible to determine which entity pays for the damage according to whether the satellite is insured or not and the type of insurance.
- Some manufacturing design errors such as the non-deployment of the solar panels or antennas. This would also require immediate post insertion inspection.

Debris and meteoroid-related events:

- Impacts on solar panels, structures and equipment: perforation and fragmentation, which can be distinguished from an ESD (see Fig. 7 below).

At 50 m **At 100 m**

Fig. 7. Simulation of an ESD and two 12 mm impacts taken at 50m and 100m distance on a solar panel

- *Validation of the risk models*

The design and cost of satellites today highly depend on different risk model. Based on these, the lifetime of a satellite is estimated. Unfortunately, validating these models is not possible through the analysis of telemetry data alone. In-situ information on the progressive state of a satellite are valuable for model verification and validation in addition to providing a better understanding of the phenomena causing failures. Repetitive and regular inspections can show how frequent an event occurs during a given period of time, which can be compared to the estimated values and models. Examples of models for a given orbit and for a given duration of time include: the number of debris impacts that can hit a satellite, the frequency of ESDs on solar panels and their number, the resistance of MLI, paint, materials and radomes to degradation on the different faces of the target satellite, and finally the thermal behavior of the target satellite. Moreover, in orbit-observations have the potential to enhance models that are based on observations made from ground (optical and RADAR) such as the estimation of debris population and sizes and their distribution across an orbit. There is a great population of small-size debris that is not detectable nor can be tracked by the optical and RADAR equipment. Thus, the collected data on the debris impacts is highly relevant to the institutions working on debris evolution models and density estimation.

- *Special event detection*

Long and/or very frequent inspections make it possible to detect and remove ambiguity regarding certain phenomena. For instance, real time ESD detection (including internal ESDs) can be done through a low-frequency unprotected receiver such as an AM receiver (amplitude modulation) and directive antenna. When an ESD occurs, radio frequency pulses are emitted, which can jam the receiver and hence be detected. Another example would be the detection of potential radio-frequency jamming from the ground. Spectrum surveillance and localization would make it possible to find and localize the jamming source, whether it is intentional or unintentional. This requires an embedded spectrum analyzer. A constellation of Orbiters using interferometry would offer more precise localization of the jamming source.

5.2.2. Inspection tasks of the Orbiter

In a nutshell, the inspection mission of the Orbiter contributes mainly to post-failure diagnosis and in some cases prevention. The latter concerns the external damage which has not yet had an impact on the inside or which is not detectable. The inspection tasks are identified according to which anomalies or events are observable by the Orbiter and also depending on the phase of the lifetime of the satellite. Each of the identifies inspection tasks are described hereafter.

<u>Regular inspection:</u> this includes taking and analyzing photos of the object. It generally requires few revolutions for a good coverage of the target and includes random or routine verifications. Debris impacts and ESDs on the solar panels can be identified along with fragmentations (due to gradual degradation for example) and other structural damage or a potential observable erosion. Localizing a debris impact on a satellite is extremely important as it can hit sensitive areas that are likely to provoke greater hazards later such as explosions (if the impact is near the thrusters for example). The regular inspection can also include the detection and localization of radio-frequency jamming in addition to the assessment of the surrounding radiation.

<u>Post-launch inspection:</u> the goal of this task is to detect potential physical anomalies related to insertion operations. An inspection could detect, as described earlier: a damage to the satellite (e.g. on structure or MLI), due to the launch conditions or interaction with other payloads, and some early system failures in post-launch operations (failure of the deployment of solar panels or antennas). A visual inspection could solve a potential conflict between the satellite operator, the satellite insurer and the launcher insurer.

<u>Surveillance of an event evolution:</u> for this task the inspection can be continuous over a certain period of time or discrete. The Orbiter could stay near a client for a long continuous inspection or performing successive inspections over a certain period of time. The former would enable a continuous real time detection of anomalies such as the frequency of Internal ESDs or the detection and localization of radio-frequency jamming. The latter proceeds to a periodic inspection in order to witness the evolution of a certain effect such as debris impacts, external ESDs or a degradation in the emissivity and efficiency of MLIs. A continuous inspection would apply more severe constraint on the design of the Orbiter, notably on the power system, as the capacity of the Orbiter to recharge its battery is limited during an inspection. The fuel budget also needs to be adapted, as the Orbiter may require many station keeping maneuvers to maintain its relative trajectory.

<u>Preparation of debris removal mission:</u> this task requires a collaboration with debris removal companies such as ClearSpace, in the context of the ESA initiative CleanSpace, and Astroscale. The goal is to inspect the debris to be removed in order to provide additional information regarding the current shape and state of the object in addition to other relevant information such as estimating the tumbling of the debris. This should highly participate in the decision-making regarding the removability of the debris, and thus it spares a potential mission failure. In other words, inspecting a debris makes it possible to anticipate and adapt the removal mission according to the current shape and state of the debris.

<u>Event-specific inspection:</u> this is considered as a pre and/or post-event inspection, where the event can be periodic such as the Perseids meteor showers (every year in August) or non-periodic such as a violent solar storm. The goal is to see the visual impacts of these phenomena on the space vehicle after the event. Scientific and technological missions could use these data to study the space environment such as the concentration of the meteoroids during the Perseids or preparing avoidance maneuvers for the following years.

<u>Object identification:</u> the goal of the Orbiter for this task is to identify an unknown object in orbit that might be a threat using the onboard payload on demand. Depending on the inspection distance, the Orbiter could identify: the nature of the object (operating satellite, rocket stage, old satellite, debris etc...) and for a satellite, its function and the operating country
<u>Space weather data collection:</u> the orbiter will be equipped with space weather instruments, seen as an opportunity to be exploited during transfer and parking orbits. The space weather data are critical at this period as the sun just entered

a high intensity cycle, which could directly cause damage to earth and space infrastructures. The monitoring of the space weather data will be beneficial to the ISSAN platform end-users.

5.2.3. Orbiter missions

The capacity of the Orbiter is estimated under several assumptions, as follow. We consider that the formats for the Orbiter is a 12U CubeSat of 24 kg. This design is a likely choice for the first and/or second generations of the Orbiter. It operates between 500 km and 1200 km of altitude for a duration of 5 years. Before an inspection, the Orbiter slowly approaches its target, on an orbit with a slightly different altitude. When the target has been acquired by the Orbiter's sensors, the Orbiter starts a formation flight around the target (see Fig. 8). The formation flight is designed so that the Orbiter can observe all sides of the target with an appropriate resolution while ensuring a low risk of collision.

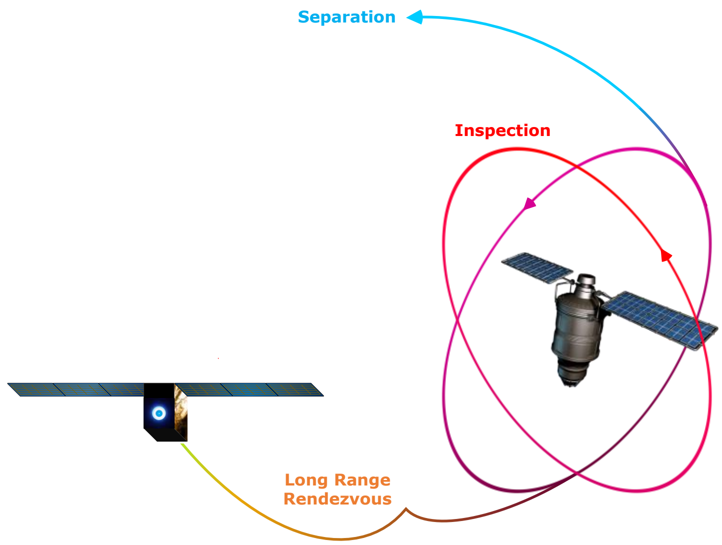

Fig. 8. Scenario of an inspection by the Orbiter, relative motion

Mission I: The Orbiter for LEO constellations (Commercial). the Orbiter can be launched around a plane of a mega-constellation in LEO, since it contains many satellites that can be inspected with few maneuvers. An Orbiter is ideally launched as a rideshare with some satellites of the constellation's plane. This simplifies the launch selection and planning and reduces the fuel cost of reaching the constellation's orbit. For a 60-satellite plane at 600 km, the separation between two consecutive satellites in the same plane is greater than 700 km, so we can consider inserting an Orbiter safely between them. This enables fuel and time effective maneuver to reach any satellite in the constellation plane with a simple phasing maneuver.

Mission II: The Orbiter for Watchdog (Defense). The Orbiter can be launched in partnership with a specific client satellite. It can maintain a short distance between itself and its companion, around a few kilometers. It uses its radar to detect approaching satellites or unidentified objects. It can regularly perform inspections on its companion to assess its state and monitor its close environment. This would enable it to detect incoming threat and works as a deterrent against potential aggressions.

Mission III: The Orbiter for orbit monitoring (Defense / Dual). A small constellation of Orbiters is deployed to monitor one or several identified orbits that represent a strategic interest. For instance, a constellation could consist in a dozen satellites that cover the SSO in LEO. They can reach any SSO with the same local time at different altitude with a relatively simple maneuver that maintains sun-synchronism. When they reach an orbit, they can perform a phasing maneuver to approach another satellite on this orbit. If a targeted object is on a SSO with a different local time as the ones from the Orbiters, then the Obiter with the closest local time may temporally leave its SSO and use the natural drift to correct its local time to match that of the targeted object (see Fig.9). For a 24-satellite constellation in 700 km SSO, each Orbiter could perform about 7 inspections in their lifetime, and any object would be reachable in about 70 days.

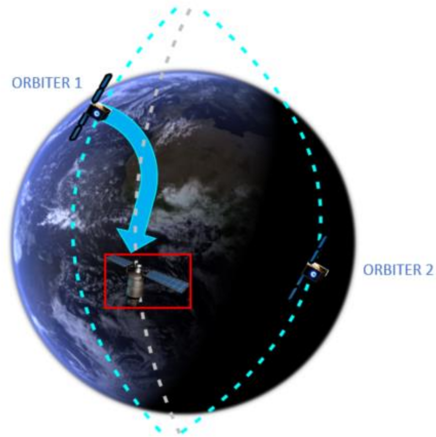

Fig. 9. Closest Orbiter changing plane to reach a suspicious target

Mission IV: Operational Permanence (Dual). The Orbiter can be used to inspect a suspicious target to identify its nature, its origin or its purpose. In case there is no Orbiter already available to inspect this object, an Orbiter can be launched for the occasion. This enables any object to be rapidly reached and inspected.

The best way to launch an Orbiter without delay and to perfectly control the insertion orbit is to use a micro-launcher, where the Orbiter would be the main payload. French opportunities like Orbital Venture plans to offer those launch starting in 2024. The opportunity to inspect a single satellite in orbit may be interesting for commercial or institutional satellite operators. The outcome of the inspection could enable to decide whether a large satellite should be deorbited to prevent debris generation.

Mission V: The Orbiter for Debris Inspection. The Orbiter can be used to inspect a debris and provide in-situ information about its state, its attitude dynamics (especially in high altitudes), shape…etc. This inspection is relevant for debris-removal companies that need to be sure they can handle the debris prior to their mission. This may prevent the launch of an expensive large debris-removal satellite through an early assessment of the feasibility of the removal with a small cheaper spacecraft.

Mission VI: Long-distance detection. This mission needs a Bolometric camera or a 2nd generation RADAR. It consists in detecting an object at a long distance from the Orbiter. It can concern potential suspicious targets to be identified in order to potentially assess the threat.

For each mission, there are typical tasks planned prior to the mission. Other tasks can be possible or opportunistic according to the needs of space actors and the constraints of the Orbiter. These are listed in the table below.

Table 1: Mission-tasks conjunction

Missions / Tasks	LEO Constellations	Watchdog	Orbit Monitoring	Operational Permanence	Debris Inspection	Long-Distance Detection
Regular	Yes	Yes	Opportunity	Opportunity	Opportunity	Opportunity
Post-Launch	Yes	Possible	Yes	Opportunity	Opportunity	Opportunity
Event-Evolution Surveillance	Possible	Yes	Opportunity	opportunity	Opportunity	Opportunity
Debris Removal Preparation	Yes	Possible	Opportunity	Opportunity	Yes	Opportunity
Event-Specific	Yes	Possible	Opportunity	Opportunity	Opportunity	Opportunity
Object Identification	Possible	Yes	Yes	Yes	Opportunity	Yes
SWE data collection	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity

- The mention “Yes” refers to the case where a task is planned as part of the mission.
- The mention “Possible” refers to a task that can be performed during a mission on demand by the client. This comes at the expense of the originally assigned tasks.
    - For example: Performing an *Event-Evolution surveillance* in a *LEO-Constellation mission* would monopolize the Orbiter for a period of time, which reduces the number of inspections previously planned during the lifetime of the Orbiter.
- The mention “Opportunity” refers to a task that can be performed during idle times of the Orbiter within another task or after a short-term mission, initiated by SpaceAble or on demand by any entity.

The possible inspection tasks and opportunities during or after a mission can be feasible or they may not be. The reasons behind the non-feasibility of certain possible tasks or opportunities are technical and operational constraints related to the capacity of the Orbiter and its design. The following constraints can be faced:

- Pointing at the same time the solar panels towards the sun for battery charging, the instruments (RADAR, camera, GNSS receiver) for a specific inspection task, or the thrusters during correction maneuvers.
- When the needed Δv to join an object for a new task is more than what is available.
- When the new task during an Idle time compromises other tasks that are already planned.
- The non-compatibility with the LOS (Loi sur les Opérations Spatiales) during a task where the Orbiter approaches its end of life, and the inspection is at a much higher altitude.

It is to be noted that the feasibility of a new inspection task is case-specific, depending on the orbital parameters and capacity of the Orbiter.

5.2.4. Case study for a LEO Orbiting constellation

This case study corresponds to Mission I described earlier for a Leo constellation. We consider a constellation with a 20-satellite plane (similar to a SpaceX constellation plane) at any LEO altitude. The number of Orbiters needed to completely cover a constellation is the same as the number of plans of the constellation (see Fig. 10). The Orbiter is a 12U format with an electrical thruster. We need to estimate the number of achievable inspections on a satellite plane with the current design of the satellite and the mission. The capacity to perform inspections will be constrained by the lifetime of the satellite, and by its fuel reserve.

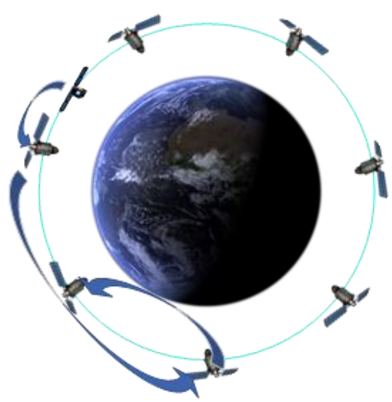

Fig. 10. The Orbiter inspecting satellites on a constellation plane

From the maneuver point of view, the life of the Orbiter, for a given plane, can be decomposed into three phases: insertion, station keeping and inspections at the constellation orbit, and deorbitation at the end of life. We will next compute the ΔV budgets [20] for each of these phases.

- Insertion

For the insertion, the cost of the maneuver depends on the targeted orbit and the orbit given by the launcher. Ideally, if the Orbiter is carried with satellites of the constellation as primary payload of a launcher, we can expect it to be delivered on an orbit close to its final destination. Since there must be some safety distance between the insertion orbit of the satellite and the constellation plane, and because all launchers have a typical maximal insertion error, we will consider that the insertion maneuver will be equivalent to an orbital change of 100 km of semi-major axis. The ΔV for this maneuver is obtained in case of a continuous thrust as follows:

$$\Delta V_{insertion} = \sqrt{\frac{\mu}{a-100}} - \sqrt{\frac{\mu}{a}}$$

With a the semi-major axis of the constellation orbit, and μ the gravitational constant.

- Deorbitation

For the deorbitation maneuver, we consider that the Orbiter must reach an altitude below 300 km. This means that the reentry will occur rapidly in less than a year, which makes sure the Orbiter will not cross the altitude of the ISS while not being controlled. The ΔV for this maneuver is obtained with:

$$\Delta V_{deorbitation} = \sqrt{\frac{\mu}{a}} - \sqrt{\frac{\mu}{R_E + 300}}$$

With $R_E = 6371\ km$ is the earth radius.

- Station keeping and inspection

After the insertion, the Orbiter must reach a parking orbit, meant for the time between the inspections. The ideal orbit is the constellation orbit. This is to prevent the plane drift between the parking orbit and the constellation orbit, if the Orbiter is at a different altitude with the same inclination. The Orbiter shall maintain its altitude and its position on the plane, to ensure a safety distance with the satellites of the constellation between the inspections. The ΔV dedicated to the annual station keeping can be estimated from the altitude.

Each inspection is composed of several phases: a maneuver to reach the phasing orbit, ballistic phase at the phasing orbit, maneuver to pass from the phasing orbit to the closing orbit, the formation flight, and finally the parting maneuver.

The cost of the maneuver to the phasing orbit depends on the difference of altitude between those two orbits. The greater the difference, the quicker the orbiter will reach the constellation satellite, but more fuel must be consumed. The duration of the inspection and the fuel consumption are the key parameter to determine the number of inspections over the lifetime of the satellite. If we note h the difference of altitude between the parking orbit and the phasing orbit, the ΔV of the transfer is obtained with:

$$\Delta V = \sqrt{\frac{\mu}{a-h}} - \sqrt{\frac{\mu}{a}}$$

We can consider that the closing altitude is almost the same as the constellation altitude, so the second transfer has the same cost. With the GNC (Guidance, Navigation, and Control) simulator, we estimate the ΔV cost of the formation flight phase at around 0.5 m/s. For margins, and to include some additional station keeping maneuvers during approach or parting, we can consider a ΔV of 5 m/s.

The duration of the rendezvous depends on the difference of altitude and the anomaly difference $\Delta\theta$ between the Orbiter and the targeted satellite. This duration is obtained with:

$$\Delta T = \frac{\Delta\theta}{\sqrt{\frac{\mu}{(a-h)^3}} - \sqrt{\frac{\mu}{a^3}}}$$

To this duration, we must add the duration of the closing and the formation flight, which we will estimate at 5 days.

The furthest satellite to reach has a difference of anomaly Δθ of π. For difference of anomaly, between π and 2π, the phasing orbit has a higher altitude than the constellation, and we can consider the problem equivalent. If we consider a constellation plane with 20 satellites, the smallest Δθ is about π/10. The more satellites in the constellation plane, the lower the anomaly difference between two consecutive satellites. An unrealistic worst-case scenario would consist in always commanding an inspection of satellites with a difference of anomaly of π. For the best-case scenario, the Orbiter would inspect the closest satellite each time, inspecting the whole constellation step by step. The ΔV allocated to the inspection is:

$$\Delta V_{inspection} = \Delta V_{tot} - \Delta V_{insertion} - \Delta V_{deorbitation} - \Delta V_{SK}$$

For each continuous maneuver, the duration is computed by dividing the ΔV by the acceleration capacity of the Orbiter. The duration allocated to the inspections over the lifetime of the satellite can be estimated from the ΔV of each maneuver. This estimation is pessimistic, as station keeping maneuver could be included in the phasing.

From the ΔV budget and time budget, we can compute the number of feasible inspections with respect to the altitude of the constellation and the difference of altitude between the constellation and the phasing orbit. The budget that is depleted the quickest is the limiting factor.

In the worst-case scenario, the difference of altitude shall be high enough to ensure the Orbiter can pass safely below or over the other satellites of the constellation. As the altitude difference increases, the number of feasible inspections due to the time constraint also increase, but the number of feasible inspections in the fuel budget is reduced. The number of feasible inspections is thus the smallest of these two numbers.

For instance, if we consider a constellation at an altitude of 600 km and our best-case scenario, the number of feasible inspections, depending on the phasing orbit, is obtained hereafter: with a difference of semi-major axis of 3 km between the constellation orbit and the phasing orbit, our ΔV budget allows for 110 inspections, and our time budget allows for 118 inspections (See Fig. 11). This means that we could theoretically perform 110 inspections, before having to deorbit the Orbiter with the remaining fuel.

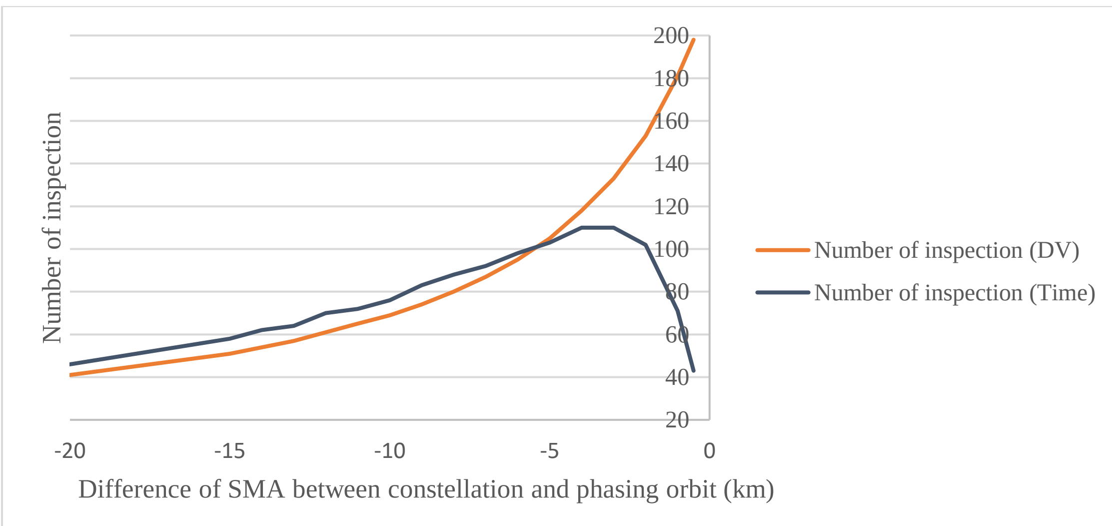

Fig. 11. Number of inspections for a constellation at 600 km

The same analysis can be performed on constellations with different altitudes, for both the best case and worst-case scenarios. The results are presented in Table 2 below.

Table 2: Number of theoretically achievable inspections

Constellation altitude	Worst case	Best case
500 km	54	121
600 km	52	119
700 km	51	117
800 km	49	115
900 km	48	113
1000 km	46	111
1100 km	45	106
1200 km	44	99

As for the safety measures regarding the rendezvous between the Orbiter and a target, an integrity system will be implemented. It monitors the navigation systems that are used and alerts the GNC system in real time when the measurements are not to be trusted. This mechanism is similar to the RAIM (Receiver Autonomous Integrity Monitoring) and ARAIM (Advanced RAIM) technologies used for aviation to monitor the GNSS navigation system.

Integrity monitoring will be implemented both for the absolute position of the Orbiter and for its relative position to the target. Two Navigation systems are considered for the first generation of the Orbiter: A RADAR and a GNSS receiver. As there is no Intersatellite link between the Orbiter and the target, the GNSS position of the target, necessary to compute the relative position, will be computed using the last received position from the ground combined with orbit propagation.

From the relative distance point of view, a protection volume around the target with a minimum safety distance to the Orbiter is defined. During the approach phase for rendezvous, the measured distance between the Orbiter and the target is compared to the minimum safety distance, making sure that the estimated distance never crosses the protection volume. As a matter of fact, reaching an integrity risk on one of the navigation systems would affect the estimated relative distance, which can lead to a collision. It is consequently very important to determine which navigation system is not to be trusted in order to use the other one for the emergency parting maneuver.

6. CONCLUSION AND FUTURE WORK

We have seen throughout this paper that the sustainability of the low earth orbit is threatened. The increasing number of satellites due to the emergence of constellation projects together with the harsh space environment elements and the design styles are accelerating the urge to develop SSA solutions and mitigation measures regarding the different risks. In this context, we have presented two complementary solutions, proposed by SpaceAble, tackling both space weather and SST in addition to in orbit inspection. On the one hand, the ISSAN platform aggregates critical space data of different sources, including data from the Orbiter on-demand, and processes this data into SWE and SST risk factors and event prediction. This makes it possible for space actors to assess different risks regarding their satellites in addition to real time monitoring and simulation. On the other hand, the Orbiter, having all the necessary software and hardware for rendezvous, is able to safely perform in orbit inspection in order to assess the general external state of a satellite. It consequently offers a way to remove ambiguity regarding some anomaly causes through in-situ inspections. This in orbit diagnosis of the Orbiter concerns thus three major services: the enhancement of production lines, mainly for satellite operators and manufacturers; dispute resolution, mainly for insurers and launchers; and pre-deorbit preparation, mainly for active debris removal actors. Moreover, as the rendezvous technology is developed for the Orbiter, the latter can be seen as an important first step that can be exploited by missions and projects working on in orbit maintenance, servicing and debris removal. This makes the Orbiter together with ISSAN a complete service capable of covering a wide range of SSA. Nevertheless, consequent efforts and research have to be made regarding the processing of SWE and SST data, which will be presented in our future publications.

7. REFERENCES

[1] "USC Satellite Database," Union of Concerned Scientists, 01 05 2021. [Online]. Available: https://www.ucsusa.org/resources/satellite-database#.WqKjWnXwaV5.

[2] "L'année spatiale 2020 : Le Bilan des lancements orbitaux," 2021. [Online]. Available: http://un-regard-sur-la-terre.org.

[3] "Satellite Anomalies," NOAA NGDC, [Online]. Available: https://www.ngdc.noaa.gov/stp/satellite/anomaly/satelliteanomaly.html.

[4] ESA, "Space Situational Awareness (SSA)," [Online]. Available: https://www.esa.int/About_Us/Ministerial_Council_2012/Space_Situational_Awareness_SSA.

[5] B. Hemenway, D. A. Galvan, W. Welser IV and D. Baiocchi, Satellite Anomalies, Benefits of a Centralized Anomaly Database and Methods for Securely Sharing Information Among Satellite Operators, RAND Corporation , 2014.

[6] D. M. Hassler, C. Zeitlin, R. F. Wimmer-Schweingruber, S. Böttcher, C. Martin, J. Andrews and F. A. Cucinotta, "The radiation assessment detector (RAD) investigation," *Space science reviews,* pp. 503-558, 2012.

[7] H. C. Koons, J. E. Mazur, R. S. Selesnick, J. B. Blake and J. F. Fennell, "The impact of the space environment on space systems," *AEROSPACE CORP EL SEGUNDO CA EL SEGUNDO TECHNICAL OPERATIONS.*, 2000.

[8] "A summary of the engineering results from the aerospace corporation experiments on the SCATHA spacecraft," in *In Proc. 6th SCTC*, 2000.

[9] V. Chandola, A. Banerjee and A. Kumar , "Anomaly Detection : A Survey," *ACM Computing Survey 43*, pp. 1-72, 2009.

[10] D. A. Galvan, B. Hemenway, W. Welser and D. Baiocchi, Satellite Anomalies, RAND Corporation, 2014.

[11] H. C. Koons and et al., "The impact of the space environment on space systems," in *Proceedings of the 6th spacecraft charging conference*, September 2020.

[12] N. Ahmad, D. Herdiwijaya, T. Djamaluddin and et al., "Diagnosing low earth orbit satellite anomalies using NOAA-15 electron data associated with geomagnetic perturbations," *Earth Planets Space*, pp. 70-91, 2018.

[13] J. Goff, "Open Source analysis of Iridium Failures and the Implications for Big LEO constellations," in *Spacecraft Anomalies and Failures Workshop*, 2017.

[14] H. Jiang, K. Zhang, J. Wang, X. Wang and P. Huang, "Anomaly Detection and Identification in Satellite Telemetry Data based on Pseudo-Period," *Applied Sciences*, 2019.

[15] NASA, "USA Space Debris Environment, Operations, and Policy Updates," Presentation to the 48th Session of theScientific and Technical SubcommitteeCommittee on the Peaceful Uses of Outer SpaceUnited Nations, 2011.

[16] J. McDowell's, "Starlink Statistics," [Online]. Available: https://planet4589.org/space/stats/star/starstats.html.

[17] M. Johnson, "NASA Robotic CARA Probability of Collision," pp. 789-4306, 2018.

[18] J. L. Foster and J. H. Frisbee, "Comparison of the Exclusion Volume and Probability Threshold Methods for Debris Avoidance for the STS Orbiter and International Space station," *NASA /TP-2007-214751. Houston, Texas: NASA Johnson Space Flight Center*, 2007.

[19] "Developing smart, antistatic wires and cables," ESA, 27 08 2019. [Online]. Available: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Developing_smart_antistatic_wires_and_cables.

[20] A. Ruggiero, P. Pergola, S. Marcuccio and M. Andrenucci, "Low-Thrust Maneuvers for the Efficient Correction of Orbital elements," in *32nd International Electric Propulsion Conference*, 2011.

[21] ESA, "ESA's Annual Space Environment Report," 2021.