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# Contribution of RAMS analyses and On Orbit Servicing missions to Post Mission Disposal success rate and sustainability of space environment

Contribution des analyses SdF et des missions de Service en Orbite au succès de la desorbitation des satellites et à la durabilité de l'environnement spatial

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**Résumé** — Cet article résume certaines études réalisées par Thales Alenia Space dont l'objectif était d'identifier comment les analyses de Sûreté de Fonctionnement pourraient amener à une meilleure décision sur la fin de vie des satellites et également comment les applications de Service en Orbite pourraient contribuer au succès des missions spatiales et donc à la durabilité de l'espace autour de la Terre.

**Mots-clés** — *durabilité de l'espace, débris spatiaux, critères de sûreté de fonctionnement, décision de fin de vie*

**Abstract**— This paper summarizes some of the studies that have been performed by Thales Alenia Space with the aim of deriving how RAMS analyses and criteria could support a better risk-awareness decision on satellite End of Life and thus to a higher compliance to Space Debris Mitigation requirements; as well as how On Orbit Servicing missions could contribute to the success of space missions and to a more sustainable use of space.

**Keywords** — *space sustainability, space debris, return of experience, RAMS criteria, End of life decision*

## I. INTRODUCTION

Space debris concern is known since more than 40 years, with the first well-known warning coming in 1978 from D. Kessler from NASA, with the identification of possible collisional cascading effects between debris already in orbit (the now so-called "Kessler syndrome"). In the last 20 years, Space Debris Mitigation (SDM) standards, guidelines or regulations [RD4][RD9][RD10] have been issued by several national and international organizations, with the following main objectives:

- To avoid the intentional release of space debris into Earth orbit during normal operations;
- To avoid break-ups in Earth orbit during operations and after the end of mission;

- To remove spacecraft and launch vehicle orbital stages from the protected regions, and in particular from Geostationary Earth Orbit (GEO), through maneuvers to a higher graveyard orbit; and in Low Earth Orbit (LEO), within 25 years after the end of the mission,
- To evaluate and control the re-entry casualty risk;
- To perform the necessary actions to minimize the risk of collision with other space objects.

Despite the introduction of these SDM requirements, today a very high number of objects is orbiting in LEO, being their main sources, among others:

- the satellites left or lost in orbit in the past;
- the debris generated by accidental explosions, collision (see for instance that between Iridium and Cosmos in 2009) or even military anti-satellite tests (see for instance that of China in 2007),
- as well as the huge number of satellite already launched and envisaged by large constellations.

All these objects pose a high risk of collision to all active satellites in orbit and in general to the sustainability of space environment, especially in already crowded regions where escalating effects could lead to an exponential increase of debris.

Some improvements are therefore needed in the near future to stabilize the evolution of the space debris population and to guarantee the safe access to space for future missions. For this purpose, several activities have been performed by Thales Alenia Space with the aim of deriving how RAMS analyses and criteria could support a better risk-awareness decision on satellite End of Life (Eol) and thus to a higher compliance to SDM requirements.

A second goal has been to evaluate if and how On Orbit Servicing (OOS) missions could contribute to the success of space missions and to a more sustainable use of space.

## II. APPROACH AND RESULTS

In order to achieve these goals, several studies have been performed by Thales Alenia Space, including a return of experience of failures occurred in orbit over the last decades and on worldwide missions in order to:

- derive some statistics on the frequency, severity and repartition per satellite subsystem and per unit of these failures and thus evaluate what is the contribution of failure scenarios, among different root causes, to the low success of Post Mission Disposal (PMD) currently observed in LEO;
- provide a better picture of the benefits and need for OOS missions (mainly refueling, maintenance and Active Debris Removal (ADR)) to extend the lifetime of spacecraft or to remove them from orbit in case of unsuccessful operations or loss of the EoL disposal capability;
- and finally to identify the RAMS criteria and the OOS missions that, retrospectively, could have helped in correctly disposing satellites in the past or those which could be required in the future.

These studies are presented in the following three sections.

### A. Post Mission Disposal unsuccess statistics

The need to improve the past and current approaches to the End of Life of satellites has been derived after analyzing the current compliance to Space Debris Mitigation standards and in particular to the requirement on the Post Mission Disposal success rate. In fact, a low success rate of the PMD is currently observed in LEO, with only limited improvements over the last years and still well below the 0.9 target, as shown in taken Figure 1 taken from [RD1].

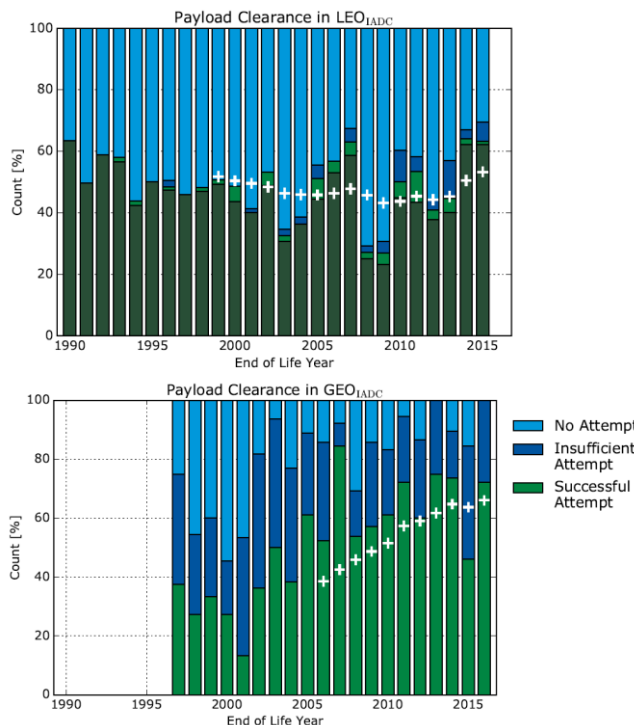


Fig. 1. Evolution of compliance to the 25 years rule for LEO and GEO satellites [RD1]

Here one can derive that in LEO, apart from those satellites naturally compliant to SDM requirement (which represent almost half of the whole population in average), most of them have not even attempted to perform EoL manoeuvres, only few of them have succeeded, while the remaining have performed some manoeuvres but not being completely successful. Among the main reasons that could justify these results, one can mention the fact that:

- before the introduction of the SDM standards and regulations, for instance [RD4], satellites were not designed to be disposed. They had not enough propellant mass and/or powerful thruster for the final orbit control;
- these SDM requirements are only “soft-laws” for most of the countries, meaning that they are only guidelines and not really binding regulations;
- wrong or too late decisions have been taken on when the disposal manoeuvres should have been started. This means that the satellite had initially the required resources and capability but that major degradations, anomalies or failures have then negatively affected the EoL operations.

On the other hand, the success rate in Geostationary Orbit (GEO) is higher and the ‘No Attempt’ much lower. This can be justified mainly by the limited slots available in GEO thus the operators did/do all their best to preserve to guarantee the continuity of their business, even if the disposal was/is not always mandatory.

Internal studies have been performed in Thales Alenia Space in order to derive what is the contribution of each of these reasons on the whole figure observed in orbit, and thus what could be the solutions and improvements ideally leading to a better success of the PDM manoeuvres in the future.

The following results have been achieved by exploiting the information of two databases.

SpaceTrak [RD2] which records and briefly describes anomalies and failures events (including their date of occurrence, severity and the involved subsystem/unit) occurred in orbit for all those satellites for which this information has been disclosed. Here additional information are provided as well, as for instance satellite mission, orbit, manufacturer, design lifetime, current age and status, etc.. As per today, this database is composed of more than four thousands records.

Celestrak [RD3] which provides updated information on orbital parameters of ‘all’ resident space objects under the Two-Line Element sets format. From here, orbit inclination, apogee and perigee altitude, orbital period and radar cross section of satellites of interest can be retrieved, as well as their status: operational, nonoperational, decayed, backup.

By comparing the current orbit of no longer operational satellites and the one required to be fully compliant to SDM requirements (recall: 25 year rules in LEO and orbit graveyard in GEO) it has been possible to distinguish the satellites which had:

- a successful attempt : the performed maneuver put the object into a compliant orbit;
- an insufficient attempt : the object performed a maneuver that failed to put it in a compliant orbit;
- or no attempt: no maneuver was performed despite residing in a non-compliant orbit.

As an example, Figure 2 and 3 shows the SDM compliance in LEO and in GEO, respectively, where each dot represents a nonoperational satellite.

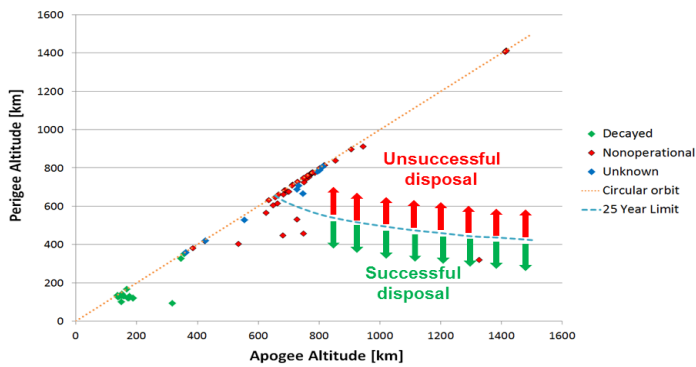


Fig. 2. Compliance to SDM requirements of recent LEO satellites

The orange line corresponds to the circular orbit where the majority of satellites are. The blue dotted curve correspond to the apogee and perigee values of a disposal orbit from which the satellite can re-enter the atmosphere in less than 25 years. The ballistic coefficient considered here to determine the circular and elliptical orbit allowing a reenter into the Earth atmosphere in less than 25 years is of  $0.005 \text{ m}^2/\text{kg}$ .

One can thus derive that all spacecraft above this curve failed in their attempt to deorbit. In addition, for those satellites in circular orbit above the blue curve, the unsuccessful disposal is associated to an inaction by the operators (no maneuver performed at all) or insufficient maneuver to reach an even lower altitude.

On the other hand, it can be observed that some satellites have successfully completed the disposal and put the satellite in an elliptical disposal orbit. This proves that operators have carried out successive maneuvers to reduce the perigee (and apogee) of their satellites.

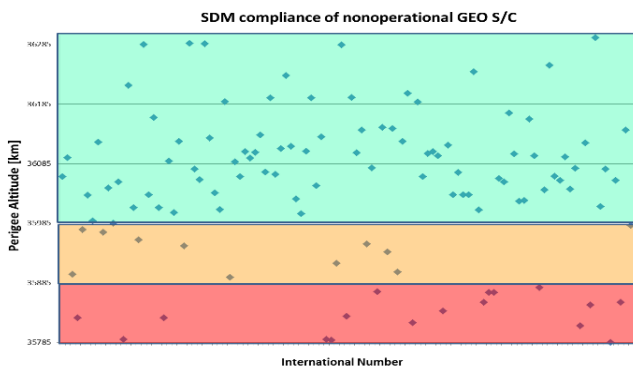


Fig. 3. Compliance to SDM requirements of recent GEO satellites

Note that International Number is not shown for GEO in order not to disclose any confidential, but unnecessarily here, information on specific satellites.

An altitude of more than 235 km above the GEO protected region, in line with [RD4] has been considered as the threshold for the success of re-orbit for GEO satellites: green zone. Satellites here have correctly performed EoL disposal operations. The orange zone between 100 and 200 km above GEO arc is linked to partially successful re-orbit, which has been often due to non-nominal scenarios. Finally, an orbit change of less than 100 km is considered as unsuccessful reorbit: red zone.

In addition, information on the mass required for the disposal versus the initial propellant budget, the failures occurred on these satellites, their severity, the involved subsystems and units, as well as some plots showing the sequence of anomalies and failures, have been derived. As an example, the failure history of two satellites, the first in LEO and the latter in GEO, with an unsuccessful disposal are provided hereafter. Subsystems are shown on Y-axis, units' name in the plot, severity as a legend, and on X-axis the ration between the satellite age when the failure occurred versus the nominal design lifetime.

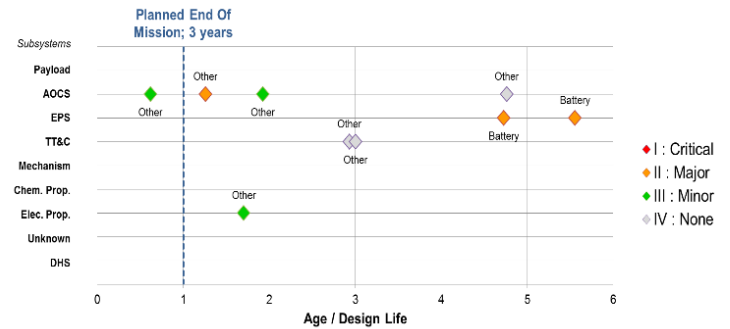


Fig. 4. Example of LEO satellite having failed its EoL deorbit

*This satellite was well beyond its nominal lifetime (almost six times more) when it has been lost and left in orbit, constituting an additional debris in LEO.*

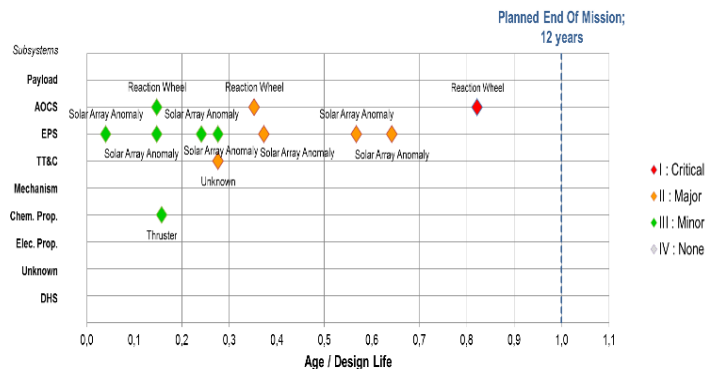


Fig. 5. Example of GEO satellite having failed its EoL reorbit

*This satellite has experiences a high number of failures during its nominal lifetime, including recurring ones on the same units, which have then impacted its capability to reorbit.*

All these data allowed to derive preliminary conclusions on main reasons for insufficient and unsuccessful disposal for some of past satellites. Almost one hundred satellites (92 to be precise) successfully launched between 1980 and 2019 and which are still in orbit around the Earth, operational or not, have been considered here. Too small spacecraft were excluded from this analysis since their peculiar design features and orbit could have biased the proposed comparative analysis. Concerning the type of mission, manned flights, experimental satellites, space station module, spacecraft delivery and resupply craft have been excluded for similar reasons.

The statistics shown below are applicable to LEO. Similar ones, even if not shown here, have been derived for GEO.

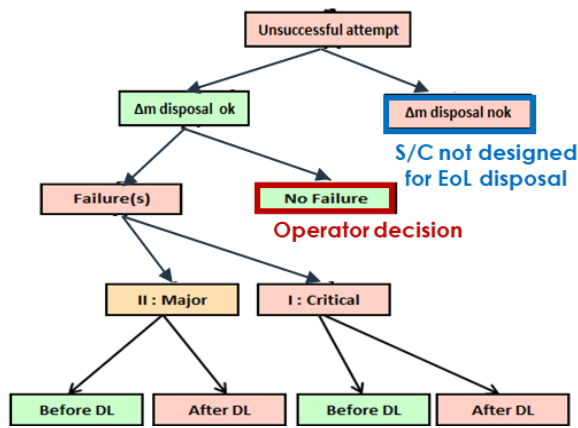


Fig. 6. Root cause analysis for unsuccessful disposal of LEO satellites

The figure below summarized the obtained results.

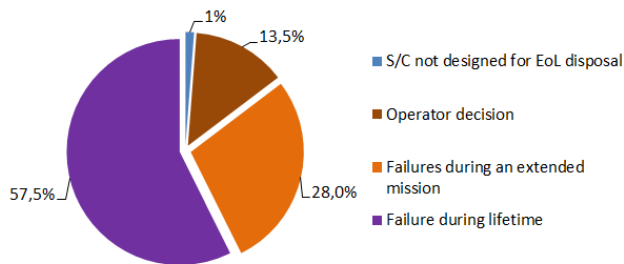


Fig. 7. Overview of results obtained for LEO satellites

It has been derived that, in most of the cases, failures occurred before the Design Lifetime (DL) (which represents about 57.5%) or during a mission extension (~28%) had a direct, or at least indirect, impact on the PMD of past satellites in LEO.

Only very few of them (~1%) have been considered as not at all compatible with the execution of EoL disposal (e.g. required propellant mass equal or even higher than the one available on board at launch). This case corresponds to the 'Δm disposal nok' shown in Figure 6, which means that the additional propellant mass required for the disposal was not compatible with the satellite design.

Finally, there are few cases in which the most plausible cause of the unsuccessful disposal has been assigned to the operator decision (~13.5%). In fact, the corresponding satellites had sufficient propellant and no (disclosed) failures that could have led to a correct disposal if the EoL decision would have been taken in the right way and at the right time.

These results allowed also to identify what would and should be changed in the future in order to improve the current low success of the EoL disposal maneuvers.

In this sense, in next years, satellite will be designed to have the EoL disposal capability (e.g. enough propellant also for the disposal manoeuvres), thus eliminating one of today contributors to unsuccessful disposal. In addition, satellite primes and operators will have to respect, if applicable to their projects, SDM standards and regulations therefore they could no longer decide not to dispose their satellites.

Thus the questions to be answered here are: how to avoid that failures would lead to an unsuccessful disposal in the future? How and when a decision to deorbit could/should have been taken from a RAMS point of view, for instance in the two cases of Figure 4 and 5?

The answers to these questions have been provided by another study, which is presented in the next section.

## B. RAMS approaches and criteria supporting EoL decision

In the frame of an R&D study funded by the European Space Agency, Thales Alenia Space has highlighted the main limitations of the current decision-making process for the life extension or start of disposal manoeuvres.

A major focus has been paid especially on the current RAMS contribution and criteria to the EoL decision. It has been explained why the current approach consisting in reassessing the compliance to the 0.9 requirement over the remaining mission lifetime does not constitute an appropriate criterion. In fact, the 0.9 threshold is reached only after several years even after the occurrence of majors failures and in addition by re-computing this probability later on during the mission, the disposal could be always delayed and, even worse, never started, even in case of a satellite having lost most of its redundancies.

This introduction has allowed to identify several axes of improvements towards a future and ideal approach where more accurate and more appropriate RAMS aspects are taken into account, hopefully leading to a better risk-awareness decision on EoL and thus to a sustainable use of the space environment.

In this sense, the Reliability and Risk awareness estimates proposed by the study team have been seen as very appropriate and useful. Several approaches have been proposed, validated and recommended to more accurately assess the probability of succeeding the EoL disposal. Among others: the consideration of occurred failures, the Return of experience and the Health monitoring on operating temperatures and margins, Prognostic based on stochastic law, engineering models and data trend analysis.

Instead of reevaluating the 0.9 criterion over the remaining lifetime as classically performed today, a Short term reliability criterion has been proposed with the aim of re-evaluating during the mission, after the occurrence of each new major failure or after a given timeframe (e.g. at least once per year), the probability of succeeding the EoL disposal in a short timeframe. It should be noticed that the probability considered here is much higher compared to the 0.9 criterion described before.

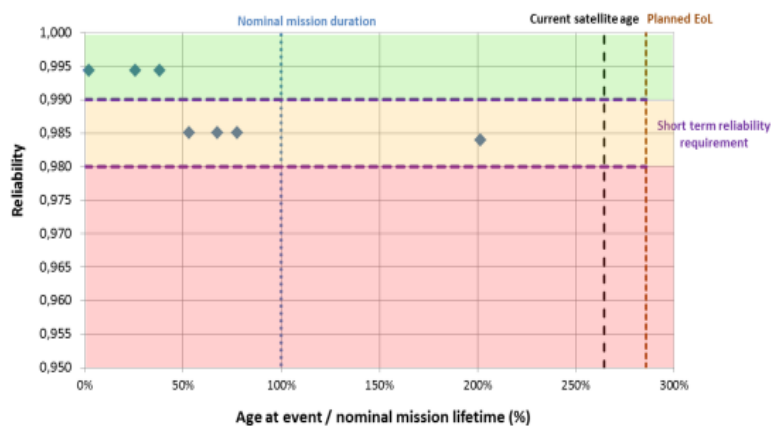


Fig. 8. Overview of the Short term reliability criterion (probability computed over one year)



Its outcome is a recommendation to anticipate the disposal when a too low probability is computed (red zone). On the other hand, if the reliability figure is still high (green zone) one could more easily decide to pursue the mission. Finally, in an intermediate case (orange zone) a special attention has to be paid, especially for those units that, if failed, could prevent a successful disposal.

In addition to these quantitative RAMS analyses, Risk Assessment analyses have been proposed for an improved decision making process since they can provide a clear picture of the current and future capability of performing the EoL disposal operations via a nominal, contingency or emergency strategy.

Here, in addition to the classical risk analyses (e.g. critical SPF list, list of Operation Life limited Items or those experiencing wear out, FMEA, PRA, etc.) a two failure matrix has been proposed to support decision-making process for the EoL. Several combinations of failures that could lead to the loss of disposal capability are analyzed, assessing the related risk and identifying potential corrective/compensatory means, already since the early phases of the satellite development process.

The matrix can be then reassessed at any point in time of the satellite nominal life in case of faults/anomalies that change the satellite configuration, expected life or operation. This analysis is therefore particularly useful for satellites with enhanced lifetime and/or that are in non-specified conditions and prone to multiple failures due to “aging”.

A simplified overview on how these quantitative and qualitative RAMS analyses could be used operationally to support the decision-making process for the EoL of satellites is provided below: the classical propellant mass criterion, as well as two additional RAMS quantitative and qualitative criteria, will be computed before the launch (see Figure 9) and reassessed during the whole mission (see Figure 10) by taking into account the functions needed for the disposal, the failures occurred in orbit and the current status of the satellite units and their Remaining Useful Lifetime (RUL).

The proposed approaches allow for a better risk-awareness decision on the End of Life and could ideally lead to a high Post Mission Disposal success rate in the future. This has been demonstrated also via the practical and operational use of these RAMS approaches for the End of Life review of two ongoing missions. Interestingly, the outcomes of those RAMS analyses have been in line with the evaluation of risks and decision to pursue the mission that were taken, with fewer justifications, by the satellite owner.

In addition, a preliminary application to previous missions, both in LEO and GEO, of the short-term reliability criterion has shown that, once its thresholds correctly defined, it could have helped in succeeding their EoL disposal, thus avoiding to leave/lose several satellites in orbit. Indeed, this is valid also for the cases shown in Figure 4 and 5, for which a recommendation to start the disposal has been raised well before their complete loss.

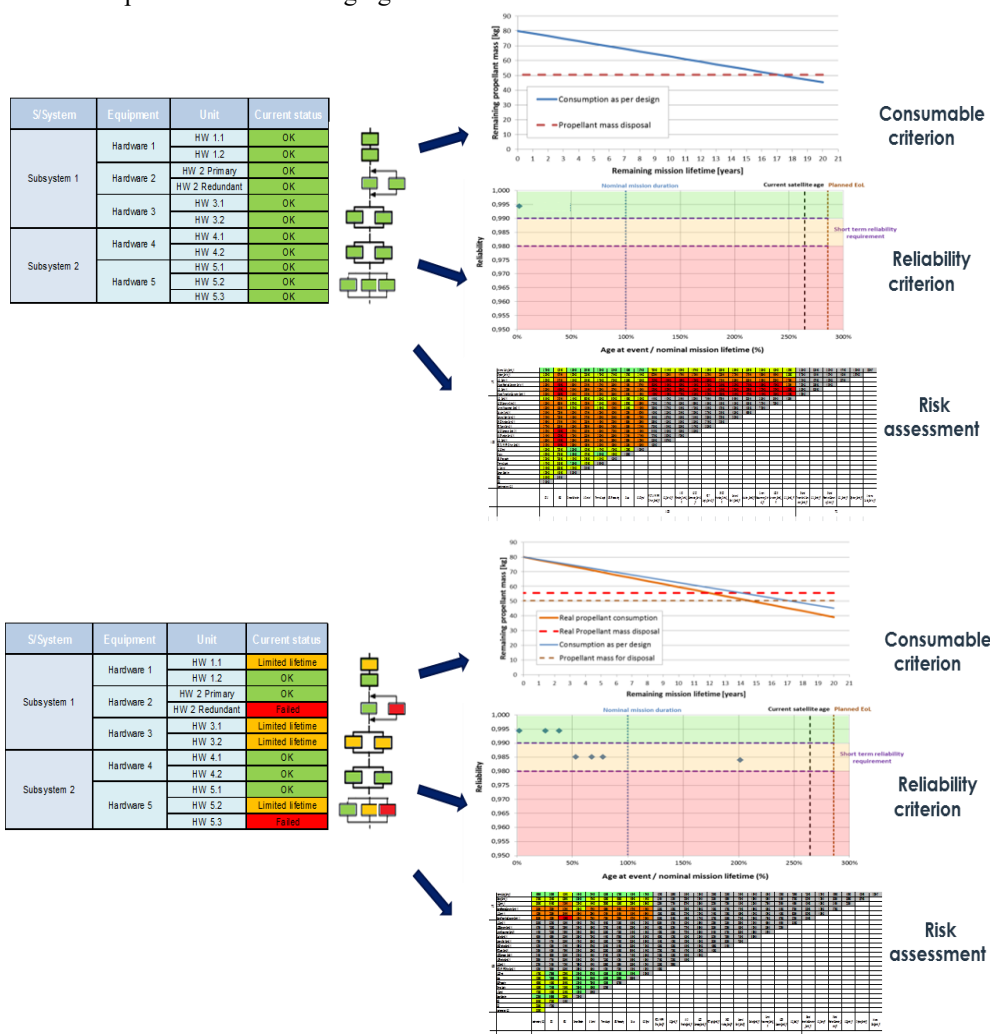


Fig. 9. Overview of the RAMS analyses and criteria computed at launch

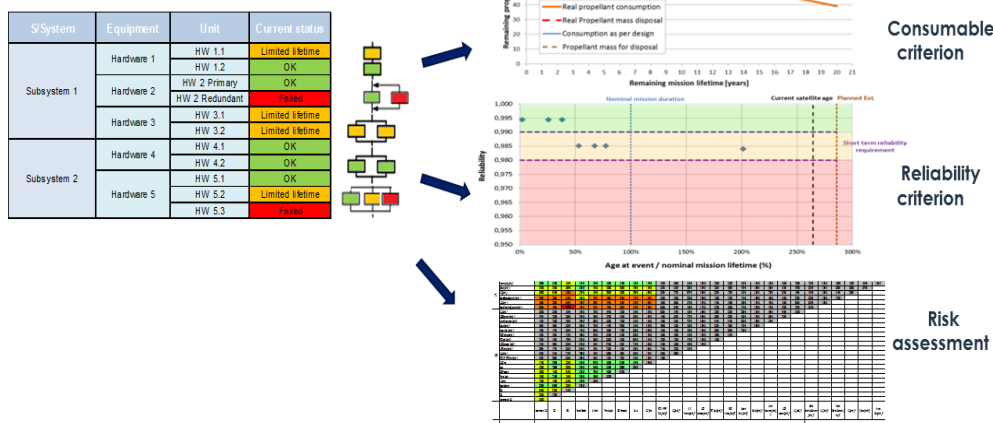


Fig. 10. Overview of the RAMS analyses and criteria recomputed during the mission

The proposed approaches and criteria will be even more important and useful for future missions for several reasons. First of all, since it is anyway required by the latest version of ISO 24113 standard [RD4] to define a specific criterion for initiating the disposal of a spacecraft, to evaluate it during the mission and to execute consequent actions if it is no longer met.

In addition, literature studies have concluded that a high PMD success rate is indispensable for the sustainability of the space, especially for large constellations, in order to limit the proliferation of space debris in already crowded LEO orbits. The application of these RAMS analyses could eventually contribute in achieving this goal.

Finally, with future in-orbit refueling missions, the propellant mass criterion could become less useful / adequate to decide when to dispose the satellite. In fact, if refueled, the propellant mass threshold would be reached always later or never ever. Therefore the RAMS criteria would be able to recommend the disposal when the risk of not being able to succeed the disposal will be too high.

To conclude, these RAMS aspects could be also used in the future not only for the EoL disposal decision but also for other applications. For instance, for On Orbit Servicing missions, presented in next section, in order to:

- assess the interest of a refueling mission for an already too 'old' satellite and to answer to the question: Does it make sense to refuel and already old (less reliable) satellite?
- to derive the need of a maintenance mission to replace the failed units or those showing a significant degradation of performance. Thus answering to these questions: Which are the hardware more likely to be replaced in orbit? And when it is more likely we should replace them?

### C. Return of experience of serviceable failures

To answer to the aforementioned questions, a recent study performed internally at TAS has shown how the return of experience of failures occurred in orbit could be exploited to better define the business case and interest of OOS missions for satellites already in orbit or those to be launched in the future.

The concept of OOS [RD7] is not new since several missions have already flown in orbit. Among most known examples one can mention the Hubble Space Telescope that was serviced five times, which included replacement of circuit boards; and the International Space Station which was assembled on orbit and continually replenished with propellant, supplies, and new modules to enhance its capabilities and provide new science opportunities. More recently, also fully commercial missions have demonstrated their OOS capability and even provided commercial services.

Indeed, several different applications may be grouped under the word OOS mission: lifetime extension, refueling, maintenance, repair, Active Debris Removal, and even manufacturing and recycling in orbit. For some of these applications the Technological Readiness Level (TRL) is sometimes still low or the business case is not fully demonstrated (yet).

In this sense, some statistics have been derived for LEO satellites with the aim of identifying what is(are) the OOS application(s) that could be potentially interesting depending on the orbital parameters and satellite status. This latter information have been derived by following the same approach of that described in section A. Figure 11 shows the results obtained for LEO satellites.

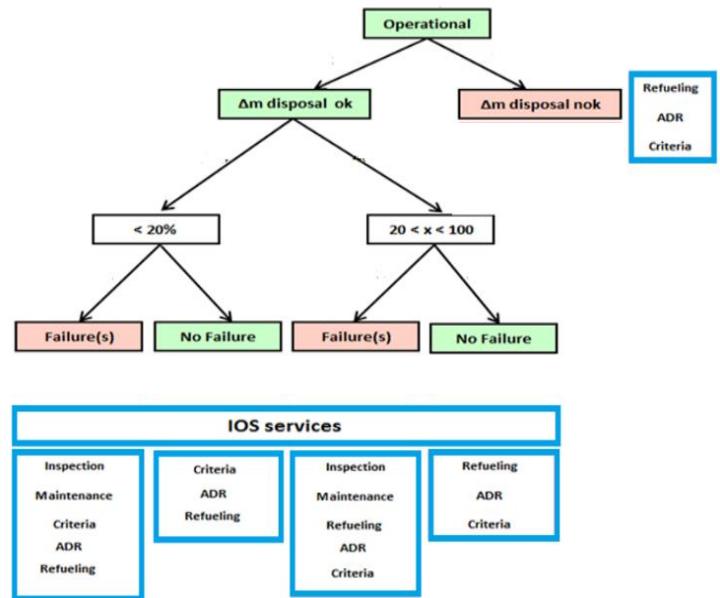


Fig. 11. OOS potential applications for currently operational LEO satellites

It has been derived here that, for those satellites without enough propellant mass to perform the disposal maneuvers (case: 'Δm disposal nok'), a refueling, if technologically possible, or an ADR mission would be needed to remove the satellite from LEO. Here RAMS can support the decision on how and when performing such an OOS mission by evaluating in detail the current and expected status of the satellite as well its reliability, by following the quantitative and qualitative Criteria presented in section B.

For those with enough propellant (case: 'Δm disposal ok') but having experienced some failures, a maintenance could be eventually performed, if technologically possible, thus allowing the satellite to perform the EoL disposal with its own means. Here RAMS analyses can support the selection of the most appropriate strategy: predictive or corrective maintenance. Alternatively, an ADR mission could be needed if the decision to repair or dispose the satellite is taken too late. In both cases health monitoring, prognostic and the reliability criterion will contribute to the decision making.

Finally, it has been derived that for some specific and limited failures, mainly those that can be 'seen' from outside the involved spacecraft, inspection missions could contribute to the identification of impacted unit and root cause analyses before further actions may be taken.

The following table summarizes the results obtained for GEO satellites launched over the last two decades. The goal of this analysis has been to support the identification and quantification of potential candidates for OOS missions.

Type of Servicing	Opportunities	Annualized
<b>Re-orbit / De-orbit</b>	18 satellites	0,9
<b>Inspection</b>	65 opportunities on 51 satellites	2,55
<b>Repair</b>	16 opportunities on 13 satellites	0,65
<b>Life Extension</b>	26 satellites	1,3
<b>Power Augmentation</b>	50 issues on 40 satellites	2
<b>Refueling</b>	14 satellites	0,7

A more in depth analysis from a RAMS point of view has led to the conclusion that for some applications, the real interesting and accessible clients are actually less than those shown before. As an example, for some inspection missions this has been justified by the fact that the root causes of some failures are already known. Thus a costly inspection mission would make less sense here.

As another example, repair missions would not have been indispensable for those satellites which have anyway other redundant unit on-board or not really cost-efficient for a satellite very close to retirement.

All these results allowed to refine the business case of OOS missions from a RAMS perspective.

### III. CONCLUSIONS

This paper summarizes some of the studies that have been performed by Thales Alenia Space with the aim of deriving how RAMS analyses and criteria could support a better risk-awareness decision on satellite End of Life and thus to a higher compliance to Space Debris Mitigation requirements.

For this purpose, a short-term reliability criterion and risk assessment matrix have been proposed, and their interest demonstrated via practical applications on on-going and past missions. Especially on this latter case, it has been concluded that these quantitative and qualitative RAMS analyses could have helped in succeeding the EoL disposal, thus avoiding to leave/loose several satellites in orbit.

In addition, some statistics have been done in order to evaluate if and when On Orbit Servicing missions could contribute to the success of space missions and to a more sustainable use of space.

To conclude, all the statistics and analyses performed here demonstrated the important role of RAMS in supporting the operators' decision on when and how to dispose the satellite, as well as to select, plan and execute OOS mission in a safe and reliable manner.

### ACKNOWLEDGMENT

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