RELIABILITY MODEL SUPPORTING MISSION EXTENSION AND END-OF-LIFE DECISIONS

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ABSTRACT

The growing number of satellites in orbit and the current deployment of large constellations of small satellites raise the problem of space traffic management, orbital debris and saturation of usual Earth orbits. Currently, about seventy percent of satellites are deorbited at their end-of-life, including only a small percentage deliberately with a propulsion system. The risks of collisions and explosions in orbit associated to the increase of debris has led to the implementation of preventive and corrective actions at national, european and international levels to ensure the availability and safety of these orbits for future space projects. Therefore, it appears necessary to choose the best moment and guarantee, with the best estimate possible, the operations of passivation and withdrawal from service for satellites at their end-of-life.

This paper presents and illustrates different approaches to improve satellite reliability model and update it regularly in order to initiate end-of-life operations at the best moment or continue the mission with a life extension. These methods are based on Bayesian, Chi-Square and Arrhenius techniques that rely on operations feedback in order to provide a more realistic risk assessment, closer to the value statistically observed in orbit.

This will lead to a better compliance to space debris national and international standards concerning end-of-life operations, as the French Law on Space Operations or the ISO on Space Debris Mitigation. These methods are also a tool for operators to choose between a withdrawal from service or a mission extension when needed. That way, it will guarantee a safe access and operations in space for future missions by limiting the proliferation of space debris in already crowded Earth orbits.

1 INTRODUCTION

The constant increase of the number of space debris – especially in Low Earth Orbits – and recent collisions between active and defunct satellites have led to the establishment of standards by several international organizations of big space nations to encourage global effort to deal with this issue. They require, among others:

- To avoid the release of Mission Related Objects into Earth orbit during the operations;
- To avoid break-ups in Earth orbits during operations and after the end of the mission by passivating all the sources of energy stored on board;
- To remove spacecraft and launch vehicles orbital stages from the LEO through a controlled re-entry or an uncontrolled one within 25 years, and GEO protected regions through maneuvers to a higher orbit of about 200km;
- To perform the necessary actions to minimize the risk of collision with other space objects.

In this context, the success of end-of-life operations is a major requirement. It directly determines the long-term evolution of the debris population in flight: all the simulations carried out by the agencies as part of the Inter-Agency Space Debris Coordination Committee (IADC) studies were carried out with a success rate set at 90% (percentage of satellite withdraw versus population of end-of-life satellites).

The update of the satellite reliability model and the resulting probability of successful end-of-life operations during the satellite life – with regard to the different events (anomalies, breakdowns, etc.) experienced by the satellite – constitutes one of the criteria for initiating an end-of-life or approving a mission extension.

2 END-OF-LIFE OPERATIONS AND MISSION EXTENSION

2.1 Description of the end-of-life operations

The service withdrawal manoeuvers include the following steps:

1. Satellite deorbitation or reorbitation to free the LEO and GEO most used orbits:

    - If the implementation is done in protected geosynchronous (GEO) regions: the satellite withdrawal operations must be such that it cannot return to the protected area naturally within 100 years;
    - If the implementation is in the protected Low Earth Orbit (LEO): the satellite withdrawal operations must be such that it must no longer be present in LEO orbit within 25 years after the end of the mission. The satellites are designed to carry out an atmospheric reentry within 25 years after their end of operational life.

2. The fluid passivation of the satellite: It corresponds to the emptying of the propellants and to the depressurization of all the pressurized systems present in the satellite, such as the chemical propulsion systems and plasma too. At the end of the fluid passivation, the resulting pressure must not exceed a few bars (in concordance with the technical regulations).

3. The electric passivation of the satellite: It corresponds to the definitive de-energization of all systems and equipment of the satellite that could either present risk for the integrity of the satellite or disturb other orbital objects. This includes:

    - The shutdown and isolation of all actuators (AOCS) such as reaction wheels or gyroscopic actuators;
    - The shutdown of all equipment capable of transmitting (RF);
    - The disconnection and isolation of the battery and of all other sources of electricity generation (solar generator for example).

The Figure 1 summaries the required end-of-life operations.

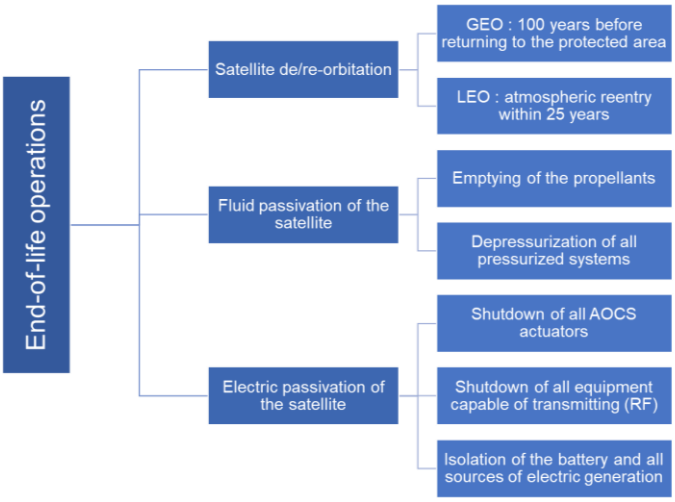

Figure 1. End-of-life operations summary

2.2 Regulations and standards

2.2.1 French Law on Space Operations

The 2008 French Law on Space Operations decrees that every operator has to carry out, for any space operation, an impact assessment on the environment, and a hazard study with a plan to manage risks and ensure safety of populations, properties, public health and the environment. The authorization process and the assessment of compliance with the Technical Regulation provides assurance that the operators have the means, resources, necessary skills and are appropriately organized to perform the operation in compliance with the law. It also allows competent authorities to verify that compliance is maintained throughout operational life of the space object up until disposal.

More specifically about end-of-life operations, the law stipulates that: "The probability of being able to successfully carry out the withdrawal operations must be at least 0.85. This probability, which does not include the availability of consumable energy resources, must be calculated before the launch over the duration of the control phase for which the system has been qualified and takes into account all systems and equipment usable for these maneuvers, their possible redundancy levels and their reliability.”.

The respect of this law is required to obtain the right to launch a satellite from Kourou. An update of these regulations is going on this year, with a possible reevaluation of this value to 0.90 as this issue becomes more and more important for the future of space traffic management.

2.2.2 International standards on Space Debris Mitigation

Space Debris Mitigation is the action of reducing the severity, seriousness and painfulness of space debris, with the main objective of insuring space sustainability for the future.
The Inter-Agency Space Debris Coordination Committee (IADC) and the International Organization for Standardization (ISO) released Space Debris Mitigation guidelines and requirements few years ago.

More specifically about end-of-life operations, in the ISO 24113 of 2019 on Space Debris Mitigation, the absolute probability of successful end-of-life operations is set at 0.90 and a "Specific criteria for initiating the disposal of a spacecraft shall be developed, evaluated during the mission and, if met, consequent actions executed.".

2.3 Probability of successful end-of-life operations

The probability of successful end-of-life operations correspond to the reliability of the chain of subsystems required to perform the operations. Before the launch, it is calculated over the mission duration. The reliability engineer conducts it in interface with project architects and usually follows the next steps:

- ✓ Identifying the end-of-life operations necessary for the studied satellite;
- ✓ Identifying the subsystems necessary to fulfill these operations;
- ✓ Evaluating the failure rates of these subsystems;
- ✓ Calculating the overall reliability of this chain of subsystems;
- ✓ Enriching the result with experience feedback, if available.

The main difficulty of the study is to have access to the failure rates of the subsystems necessary for these operations. Therefore, it is better to anticipate this calculation from the preliminary design stages, by choosing components and subsystems for which the suppliers have carried out reliability studies, tests or have already flown long enough.

2.4 Mission extension

Currently on CNES satellites, the probability of successful end-of-life operations is evaluated before the launch – in order to obtain the authorization to launch the satellite, and at the end of the nominal mission – in order to obtain the validation for a mission extension.

The French Space Agency is currently updating its regulation and a re-estimation of this probability taking into account the failures and anomalies seen by the satellite during the nominal mission will be required in order to obtain a mission extension for all French operators. The same criteria of a probability higher than 0.90 will be used to obtain the mission extension authorization.

This probability of successful end-of-life operations – along with the remaining propellant mass – therefore constitutes one of the principle criteria to choose the best moment and guarantee with the best estimate possible the operations of passivation and withdrawal from service for satellites at their end-of-life.

3 SATELLITE RELIABILITY MODEL

3.1 Theoretical Reliability

The theoretical reliability assessment of a satellite is based on the following hypotheses:

- The components are assumed to have constant failure rates λ over the mission duration (they are in their qualification area) and independent failures.
- The exponential law is used to calculate the reliability (R) according to the Equations 1, 2 and 3:

- For a single point of failure:

$$R_{SPOF} = e^{-\lambda_{ON}*t} \quad (1)$$

- For an active redundancy:

$$R_{Active}(m/n) = \sum_{i=0}^{n-m} \frac{n!}{i!(n-i)!}(1 - e^{-\lambda_{ON}*t})^i * (e^{-\lambda_{ON}*t})^{n-i} \quad (2)$$

- For a passive redundancy:

$$R_{Passive}(m/n) = e^{-m*\lambda_{ON}*t}\left[1 + \sum_{i=0}^{n-m} \frac{(1-e^{-\lambda_{OFF}*t})^i}{i!} \prod_{j=0}^{i-1}(j + m\frac{\lambda_{ON}}{\lambda_{OFF}})\right] \quad (3)$$

- The failure rate λ_{OFF} of a subsystem that is not in operation is assumed to be 1/10 of the failure rate λ_{ON} for Electrical, Electronic and Electromechanical (EEE) components;
- For subsystems with a use rate α other than 100%, an equivalent failure rate is calculated using the Equation 4:

$$\lambda_{equipment} = \alpha * \lambda_{ON} + (1 - \alpha) * \lambda_{OFF} \quad (4)$$

However, the results of this method are always pessimistic regarding with the real performances of the satellites. Indeed, the main source of uncertainty of the method comes from the reliability handbooks (MIL-HDBK-217F or FIDES).
The Military Handbook on Reliability Prediction of Electronic Equipment (see [8]) is the most widely used empirical reliability prediction model for electronic equipment. This military handbook was developed in 1961 with the purpose of establishing and maintaining consistent and uniform methods to estimate the inherent reliability of military electronic equipment and systems. However, it is not updated since 1995, and incomplete since new components, technologies and quality improvements are not covered.
As a result, actual in-orbit performance has often showed largely conservative results leading to potential overdesign, reduced performance and cost effectiveness of satellite design. Some R&T had been conducted by the French agency and Space industrials – Airbus Defence and Space and Thales Alenia Space – in order to update and revitalize the MIL-HDBK-217F standard in recent years and a Reliability models extensions user Guide has been published, see [9].

3.2 Mathematical models based on experience feedback

3.2.1 Bayesian Method

A forecast estimate of a subsystem reliability can be consolidated by taking into account the effective operating life of identical subsystems, operating since its launch in similar environments and conditions of use (including temperature), by application of a Bayesian model.

It is possible to determine a new failure rate $\lambda_{bayesian}$ using:

- the theoretical failure rate λ calculated previously (in FIT),

- the total operating time T in flight of identical subsystems (the number of hours is multiplied by 10^{-9} for consistency with λ in FIT),
- the number of failures k encountered by the subsystem during T,
- the confidence level (generally taken at 60%, for which $\alpha_0 = 1.765156$):

$$\lambda_{bayesian} = \frac{\alpha_0 + k}{\frac{\alpha_0}{\lambda} + T} \qquad (5)$$

Remark: The demonstration of this equation is in the previous paper on this subject, see [1].

It allows to combine a theoretical reliability with operation results of similar equipment in order to consolidate the initial satellite reliability model (calculated before the launch) – as shown for the case of TARANIS in chapter 4.

The Bayesian method is also the most used to update the reliability model with the events and failures encountered during the satellite lifetime.

3.2.2 Chi-Square Method

Another classic approach to calculate a failure rate with the experience feedback – composed of tests or in orbit data – is the Chi-Square distribution. When assuming that the life of the device follows an exponential law with constant failure rate λ and that failures are independent, the statistic "twice the total test time T divided by the mean life 1/λ" is distributed as a Chi-Square χ^2 (α, n) where α is the confidence level and n the degree of freedom. The equation 6 defines the estimator of the deducted Chi-Square failure rate:

$$\lambda_{Chi-Square} = \frac{\chi^2_{1-\alpha}(2*k+2)}{2*T} \qquad (6)$$

With:
- Total operating time T in hours;
- Level of confidence 1-α (often taken equal to 60%);
- Number of failures observed k.

Remark: The demonstration of this equation is in the previous paper on this subject, see [1].

This model is less used and only useful when many subsystems operating data is available – for satellite constellations using the same platform for example. When the total operating time is small, the estimation is pessimistic and not reflecting the reality. This method will also be illustrated in the chapter 4 with the satellite TARANIS, using a generic microsatellite platform Myriade with a lot of experience feedback.

3.2.3 Arrhenius method

The Arrhenius method allows updating the subsystem failure rates during the satellite lifetime by taking into account the real operating temperatures.
The acceleration factor AF between two temperatures is defined in Equation 7:

$$AF = e^{\left(\frac{-E_a}{k} * \left(\frac{1}{T_1} - \frac{1}{T_0}\right)\right)} \quad (7)$$

With:
- The activation energy E_a in eV;
- The Boltzmann constant k;
- The reference temperature T_0;
- The real temperature T_1.

With this acceleration factor, it is possible to calculate the new failure rate of the system by applying the Equation 8:

$$\lambda_{T_1} = \frac{\lambda_{T_0}}{AF} \quad (8)$$

The Figure 2 summaries the three mathematical models – previously described – used to update the reliability model with experience feedback:

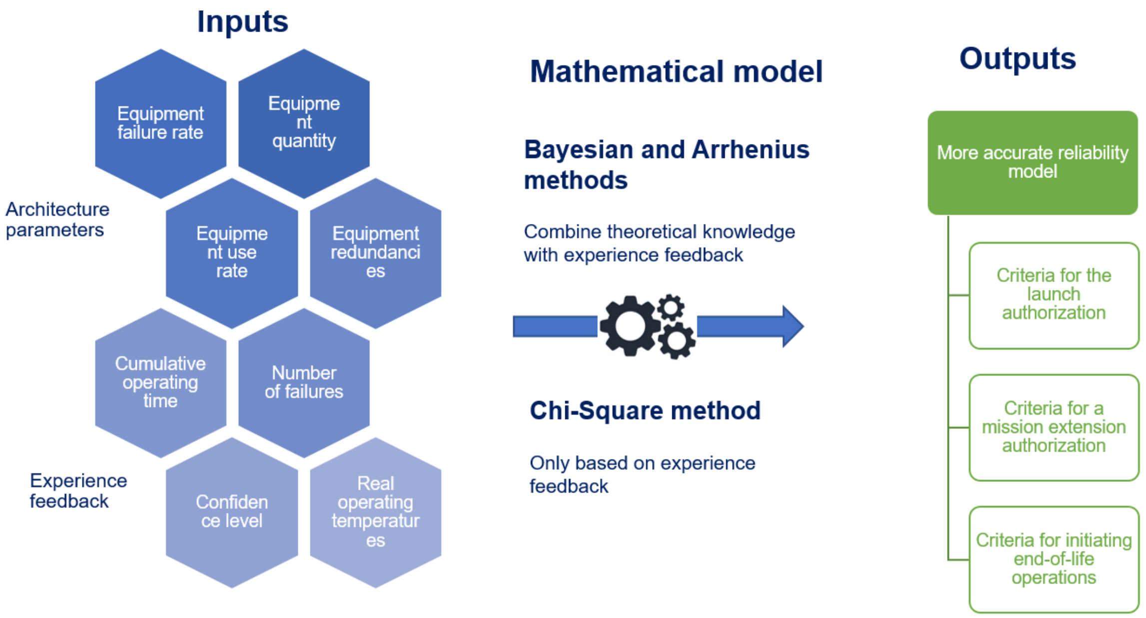

Figure 2. Reliability model summary

4. TARANIS EXAMPLE

4.2 TARANIS presentation

TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) was an observation microsatellite of the French Space Agency CNES which would have studied the transient luminous events that form over the clouds during thunderstorms around the globe.
The TARANIS mission was dedicated to study the magnetosphere, ionosphere and atmosphere coupling via transient processes and would have observed all the emissions above thunderstorm and allowed to simultaneously measure:

- Transient Luminous Events;
- Terrestrial Gamma-ray Flashes;
- Electric and Magnetic emissions;
- Runaways electrons beams.

TARANIS would have been placed on a sun-synchronous orbit at an altitude of 676 kilometers with a mission duration in orbit counted as follows:

- Satellite launch, early orbit phase and fine positioning: 0.5 month;
- In-flight commissioning: 2.5 months;
- Routine phase: 45.0 months;
- Mission extension: 12.0 months;
- Disposal phase: 2.0 months.

Unfortunately, in November 17 2020, the Vega flight VV17 failed to place the satellite in orbit and the mission was lost. The problem was due to an inversion of two cables carrying control signals to the thrust vectoring actuators on the fourth-stage engine. With the guidance signals going to the wrong actuators, the launcher was uncontrollable and began to tumble.

4.3 TARANIS Architecture

The TARANIS satellite was associating a Myriade microsatellite platform and a payload including the scientific instruments.

The following instruments - showed on Figure 3 - constituted the TARANIS scientific payload:

- MCP: a set of two cameras and three photometers measuring the luminance in several spectral bands at high resolution;
- XGRE: a set of three detectors to measure high energy photons (20 keV to 10 MeV) and relativistic electrons (1 MeV to 10 MeV);
- IDEE: a set of two electron detectors to measure their spectrum between 70 keV to 4 MeV together with their pitch angle;
- IME-BF: a low frequency antenna to measure the electric field to a frequency up to 3.3 MHz;
- IME-HF: a high frequency antenna to measure the electric field at frequencies of 100 kHz to 30 MHz;
- IMM: a tri-axis magnetometer to measure the magnetic field.

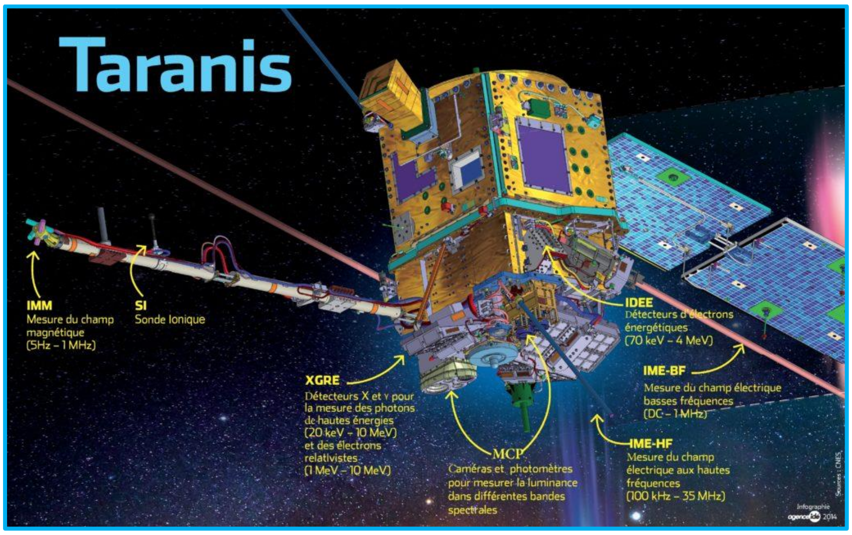

Figure 3. TARANIS scientific payload

The TARANIS platform was based on the Myriade microsatellites series recurrent product line, using a new 200kg structure. It included the support functions for in flight operations as provision of electrical power, command and data handling, telecommunications, thermal control and propulsion for orbit maneuvers.

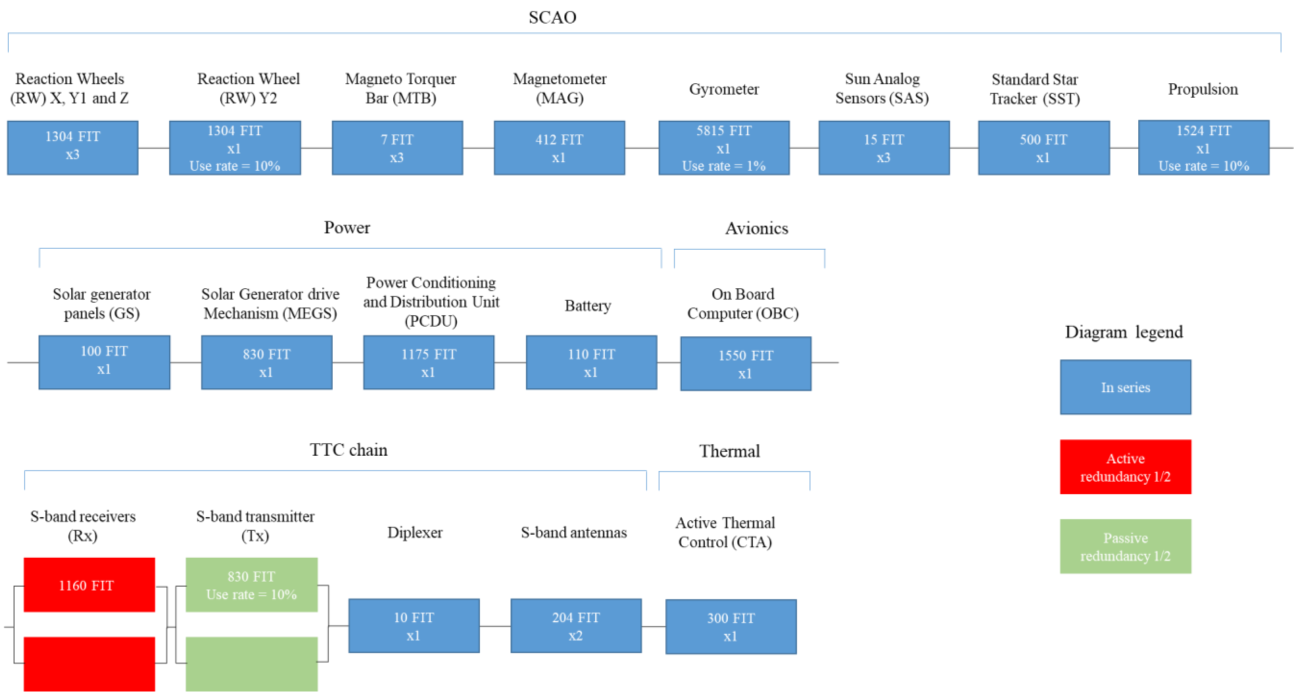

Figure 4. Reliability Block Diagram of the TARANIS platform

4.3 TARANIS end-of-life operations

The satellite would have been deorbited and then passivated at the end of the TARANIS mission, In this case, the deorbitation consisted in lowering the orbit altitude of the satellite, allowing it to enter the atmosphere in less than 25 years. In order to be able to perform these deorbiting maneuvers, the Payload and interface circuits on the Platform side were not necessary, but all other satellite functions and subsystems were required.

The fluid passivation would have been ensured by a procedure allowing the emptying of the propellant that does not differed from the nominal procedures. The electrical passivation would have been done by a discharge of the battery, an orientation of the GS back to the sun and an opening of the GS sections.

The probability of successful end-of-life operations corresponded to the reliability of the platform. This probability needed to be better than 0.85 at the end of the mission duration in order to obtain the right to launch the satellite. A one-year mission extension would have been also envisaged.

4.4 TARANIS reliability model

4.4.1 Theoretical Reliability

For the platform subsystems, the development was largely based on equipment purchased "off the shelf" (COTS), for which the directives given to manufacturers were to deliver for information – when it existed – the reliability documentation available from previous programs.
Thus, the failure rates of the subsystems considered in Figure 4 come either from supplier data, from calculations with the Military Handbook MIL-HDBK-217F or from analogies with other programs.

Using the failure rates of the Figure 4 and Equations 1, 2 and 3, the theoretical reliability of the TARANIS platform was **0.68**. This number was very low and pessimistic in comparison with the results of previous missions based on a Myriade Platform. It was under the requirement of 0.85 previously defined.

4.4.2 Bayesian Reliability

The Bayesian method previously defined has been used to consolidate the theoretical failure rates. It allowed combining the theoretical values from the previous part with the Myriade experience feedback from previous missions. At the moment of the study, the cumulative time in operating orbit of the Myriade platforms reached more than 53 years of operation (T = 469 440 hours) without permanent failure incrementing the k parameter of the Equation 5.

For subsystems in several copies, their number multiplied the overall operating time. The model also took into account the use rate, when it was different from 100%. Some subsystems such as the solar generator drive mechanism and the star tracker not being present on Myriade "minimal" type platforms, the operating time took into account was a little bit less than 31 years (T = 269 000 hours). For Myriade wheels, the cumulated return of experience reached more than 145 years (T = 1 273 080 h).

Thus, using Equation 6, the Bayesian method obtained the failure rates of the Table 1, which were much better.

Table 1. Bayesian reliability data of the TARANIS platform

System	Subsystem	Failure rate [FIT]	Use rate	Quantity	Cumulative operation time	New Failure Rate [FIT]
Avionics	OBC	1550	100%	1	469 440	1100
Power	GS	100	100%	1	469 440	98
	PCDU	1175	100%	1	469 440	895
	Battery	110	100%	1	469 440	107
	MEGS	830	100%	1	269 000	737
TTC chain	Rx	1160	100%	2	938 880	887
	Tx	830	10%	2	93 888	812
	Antennas	204	100%	2	938 880	184
	Diplexer	10	100%	1	469 440	10
Thermal	CTA	300	100%	1	469 440	278
SCAO	RW (X, Y1 et Z)	1304	100%	3	1 273 080	672
	RW (Y2)	1304	10%	1	1 273 080	672
	MAG	412	100%	1	469 440	371
	MTB	7	100%	3	1 408 320	7
	SAS	15	100%	3	1 408 320	15
	SST	500	100%	1	269 000	465
	Gyrometer	5815	1%	1	4694	5727
	Propulsion	1524	10%	1	46 944	1465
Probability of successful end-of-life operations after nominal mission						0.76

Recalculating with these new failure rates, the platform reliability on the mission duration (and the resulting probability of successful end-of-life operations) was better: **0.76**.

In order to improve this estimation, it was also possible to group all the subsystems in series by adding their failure rates and then applying the Equation 5 to the new "In series block". In this case, the new results of reliability were better: **0.87**. It demonstrated the requirement of a reliability better than 0.85 over the 4 years and 2 months of nominal mission.

4.4.3 Chi-Square Reliability

For a platform with as much return of experience as Myriade, the Chi-Square model was the most efficient to obtain a representative reliability. By application of the Equation 6 with T = 269 000 h of Myriade working time without impacting permanent failure and a confidence level of 60%, it was possible to obtain the global $\lambda_{Chi-Square}$ and calculate the overall reliability: **0.88**.

The Chi-Square model allowed demonstrating the probability of successful TARANIS end-of-life operations that was required to obtain the authorization to launch the satellite.

4.4.4. Comparison between reliability models

The Figure 5 is a comparison of TARANIS reliability obtained with theoretical calculations, Bayesian and Chi-Square models:

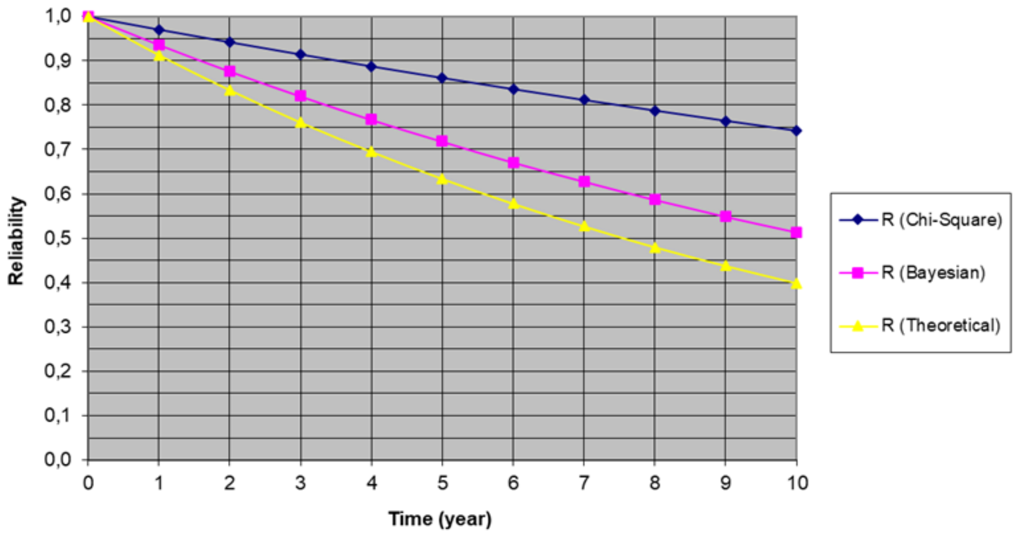

Figure 5. TARANIS probability of successful end-of-life operations

4.5 TARANIS mission extension

As the launch of TARANIS was not successful, this part has been conducted as an example with three theoretical scenarios:

1. No major failure impacting the reliability during the nominal mission;
2. Apparition of a permanent anomaly on the X-reaction wheel inducing oscillations around X-axis;
3. Permanent failure of one nozzle due to a failure of the solenoid valve commanding the nozzle and same reaction wheel anomaly as in 2.

The reliability model presented in Table 2 has been updated with additional 4 years and 2 months of mission and the theoretical scenarios previously defined.

Table 2. Reliability data of the TARANIS platform for the three scenarios

System	Subsystem	Theoretical failure rate	Cumulative operation time	Failure Rate scenario 1	Failure Rate scenario 2	Failure Rate scenario 3
Avionics	OBC	1550	505 969	1073	1073	1073
Power	GS	100	505 969	97	97	97
	PCDU	1175	505 969	879	879	879
	Battery	110	505 969	107	107	107
	MEGS	830	305 529	726	726	726
TTC chain	Rx	1160	975 409	707	707	707
	Tx	830	102 122	792	792	792
	Antennas	204	975 409	183	183	183
	Diplexer	10	505969	10	10	10
Thermal	CTA	300	505969	276	276	276
SCAO	RW (X, Y1 et Z)	1304	1 386 320	644	1009	1009
	RW (Y2)	1304	1 386 320	644	1009	1009
	MAG	412	505969	368	368	368
	MTB	7	1 517 907	7	7	7

	SAS	15	1 517 907	15	15	15
	SST	500	305 529	460	460	460
	Gyrometer	5815	5059	5720	5720	5720
	Propulsion	1524	50 597	1460	1460	2195
Probability of successful end-of-life operations		after a 1 year mission extension		0.937	0.928	0.927
		after a 2 years mission extension		0.879	0.861	0.859

As shown on the Figure 6, in the three scenarios the probability to have a successful disposal after 1 year mission extension was better than 0.90, but not for a 2 years mission extension.

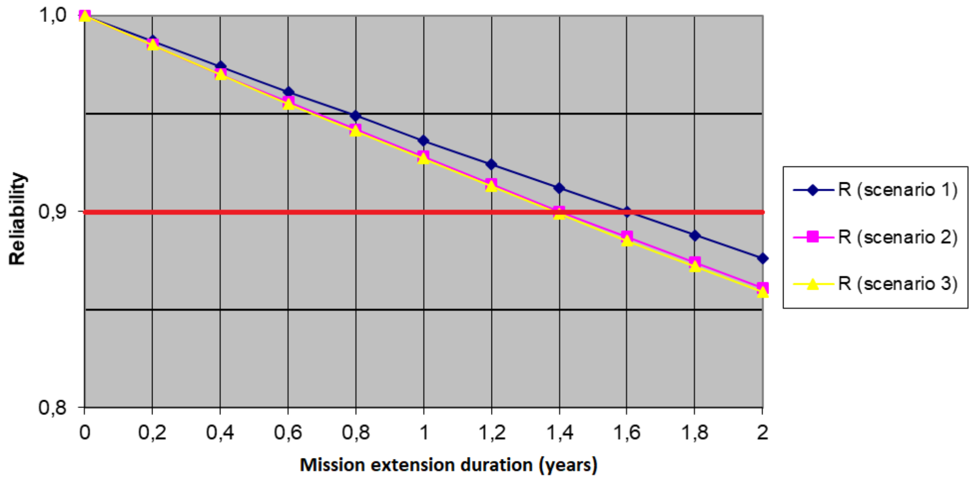

Figure 6. TARANIS probability of successful end-of-life operations after mission extension

5 CONCLUSION

Satellite successful end-of-life operations and compliance to international Space Debris Mitigation requirements are issues of importance for a space agency as the CNES, which is currently updating its technical regulation and is ready to propose new standards internationally.

The different mathematical models presented in the publication overpass uncertainties of the current reliability models using experience feedback. They are expected to lead to more realistic results and therefore to better decisions for the choice between initiating end-of-life operations or a possible mission extension. Indeed, being able to dispose a satellite in a safe and reliable manner has a fundamental importance in order to limit the exponential proliferation of space debris in already crowded orbits.

The remaining main line of research concerning the subject of this paper concerns the modeling of the reliability outside the equipment qualification domain. Beyond this qualification period, components are subjected to various wear phenomena, needing a specific model of degradation for each subsystem.

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