RAMS AND FDIR METHODS IN SUPPORT TO ZERO DEBRIS APPROACH

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08/10/2024

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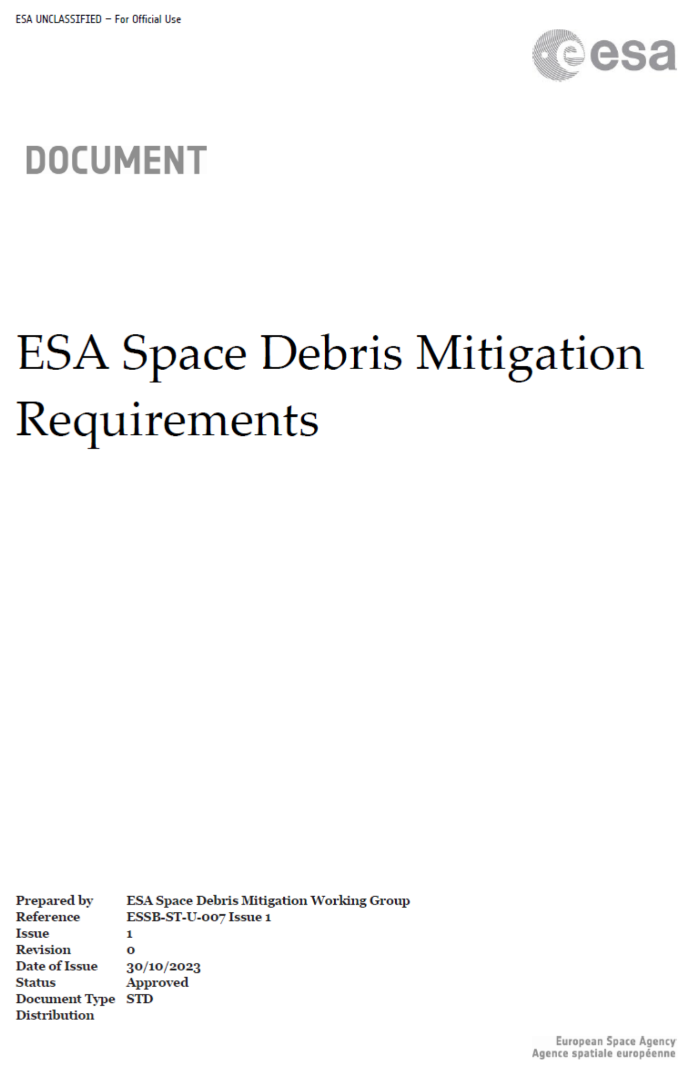
The presentation highlights how the ESSB-ST-U-007 fits within the frame of the recently developed ESA RAMS map and clarifies what RAMS and FDIR analyses, tools, and methods are required to show compliance with the ESA Space Debris Mitigation Standard (ESSB-ST-U-007).



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DOCUMENT

ESA Space Debris Mitigation Requirements

Prepared by	ESA Space Debris Mitigation Working Group
Reference	ESSB-ST-U-007 Issue 1
Issue	1
Revision	0
Date of Issue	30/10/2023
Status	Approved
Document Type	STD
Distribution	

European Space Agency
Agence spatiale européenne

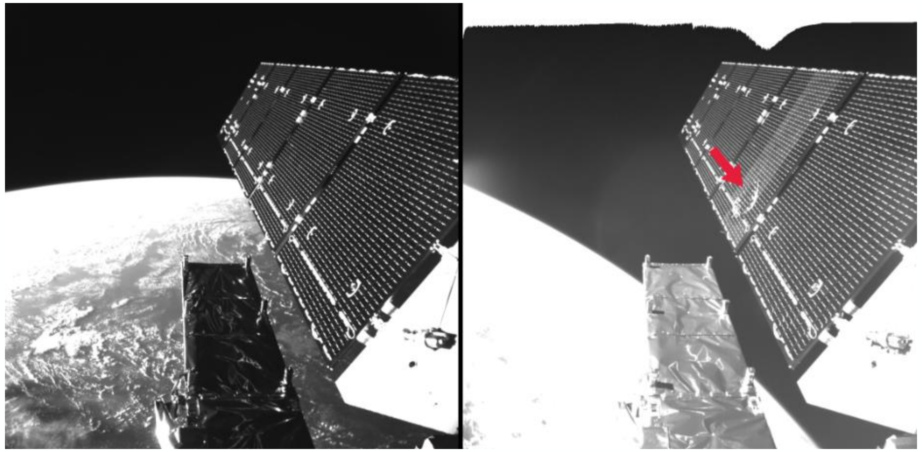
Introduction

- The sustainability of space is a critical concern in the evolving landscape of space missions, including Earth Observation and broader space exploration and utilization.
- The European Space Agency (ESA) leads the effort to combat space debris with its Zero Debris Policy (ZDP) and Space Debris Mitigation Requirements (SDMR).
- ESA's Zero Debris Policy is a commitment to achieving 'net zero pollution' for objects in space by 2030, as stated by ESA Director General Josef Aschbacher .
- The policy is supported by the ESA standard ESSB-ST-U-007, which sets clear requirements for realizing the Zero Debris vision.

Credit: Spacejunk3D, LLC

Importance

- **Growing Risks**: The increasing number of non-functional satellites in Earth's orbit presents significant risks to both current and future space missions.
- **Dead Satellites**: These are satellites that have reached the end of their operational life but have not been properly disposed of, contributing to space debris.
- **Smaller Debris**: Debris smaller than 10 cm, often resulting from collisions or micrometeoroid impacts, should not be overlooked as they are equally hazardous.
- **Call to Action**: Proactive measures are required to address both large, non-operational satellites and smaller debris to mitigate the expansion of space debris.



Sentinel-1A fragment impact in space

RAMS in SDMR

Successful Disposal

Reliability of disposal during design (SRR-QR/AR)

Reliability of disposal during operations (for EOL decision or LE)

FTA (if applicable) where need of combinations of failure

FEA/FMEA/FMECA (indirect contribution)

Mission Extension Assessment

Re-assessment of disposal **reliability**

In order to check if disposal requirement is still being met.

Return-of Experience – for future work and lessons learned

Passivation

Design of means implemented for **passivation**

Computation of **reliability of passivation** (during design and in-orbit)

FEA/FMEA/FMECA

FTA (if applicable) where need of combinations of failure

Accidental break-up

FEA/FMEA/FMECA for failure modes of units of concern

FTA (if applicable) where need of combinations of failures

Reliability prediction for failure rates of units of concern

Accidental Collision Probability Level (for CPO)

Feared Event Analysis (only in early phases of design, in later phases it is covered by FTA)

FTA having the top feared event as “collision”

NOTE: ACPL refers only to known objects

NOTE: for computation of ACPL, FTA is not sufficient, a mission analysis for each critical mission phases is also required, including for contingency.

FDIR in SDMR

Adequate implementation of health monitoring


DOCUMENT

SAVOIR FDIR Handbook

SAVOIR


ECSS-E-ST-10C Rev.1
15 February 2017

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

System engineering general requirements

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

FDIR Handbook maintenance

Through periodically updated provision of guidelines for effective and adequate FDIR designs and processes in satellite missions

Standardization of FDIR

ECSS

Intended to provide clear requirements for effective and adequate FDIR design and implementation in space missions

FDIR during operations (collection of data for future technologies)

Health monitoring techniques based on in-orbit return of experience or live experience:

Prognostics

Health monitoring:

Re-assessment of all relevant updated **RAMS** data package
and
analysing of **in-orbit failures** including
FDIR performance

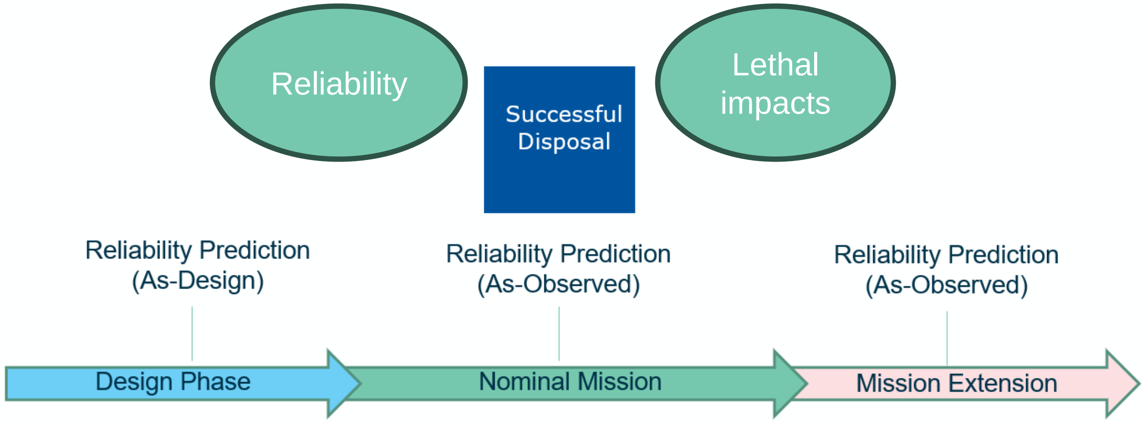
Failure Prognostics:

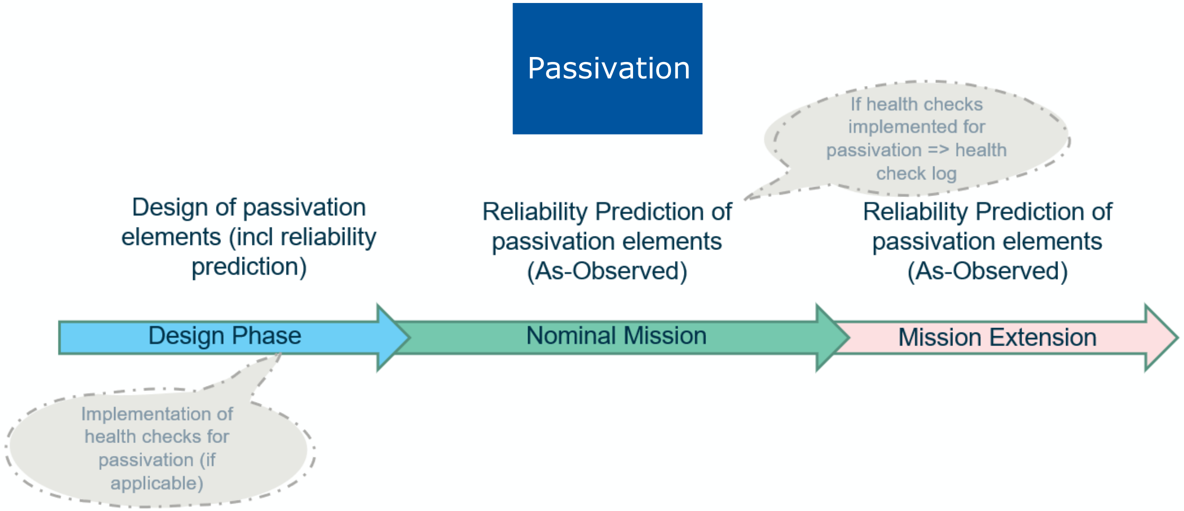
Making use of in-orbit data for **failure prediction** and **prevention** (AI/ML)

RAMS and FDIR requirements from ESSB-ST-U-007

- **Probability of Successful Disposal (reliability contribution)** - *The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above 0,9 through to end of life, including the contributions from system reliability and from collisions with space debris or meteoroids preventing the successful disposal*
- **Probability of accidental break-up during normal operations** - *The accidental break-up probability of a spacecraft or launch vehicle orbital stage in Lunar orbit shall be less than* 10^{-3} *until its end of life*
- **Passivation** - *A spacecraft or launch vehicle orbital stage operating in Earth orbit shall be designed to guarantee a probability of successful passivation through to the end of life of: 1. At least 0,90, 2. At least 0,95, when operating in the LEO protected region in an orbit with a natural orbital decay duration longer than 25 years, 3. At least 0,95, when operating in the GEO protected region*
- **Collision risk (FTA component)** - *The probability of unintentional contact between space objects because of close proximity operations, or formation flying, in Earth orbit, shall be below* 10^{-4}*.*
- **Health monitoring** - *The developer and operator of a spacecraft operating in Earth orbit shall implement failure prognostic methods for anticipating possible failures and wear-out trends.*

RAMS requirements from ESSB-ST-U-007





- **Disposal Probability**: at least 90% probability of successful system disposal (including lethal impacts but also potential failures of the disposal elements).
- **Immediate Disposal**: Prefer quick disposal post-mission to reduce on-orbit break-up risk, using the space system's propulsion capabilities.
- **Compliance Across All Systems**: Ensure all space systems, even those relying on natural decay, meet the disposal probability requirement.
- **Supporting Analyses:**
  - FMEA
  - Reliability and FTA (when relevant)

- **List Passivation Elements**: subsystems or components that need passivation (i.e. tank, batteries, etc)
- **Quantify Passivation**: Assign values or ranges to each element, from empirical data or engineering judgment.
- **Mathematical Modelling**: Use mathematical models to calculate the overall passivation probability
- **Validation and Calibration**: Compare residual risk assessment with actual data or simulation results

RAMS requirements from ESSB-ST-U-007

Accidental break-up

The probability of accidental break-up of a spacecraft or launch vehicle orbital stage in Earth Orbit shall be less than 10^-3 until its **end of life**.

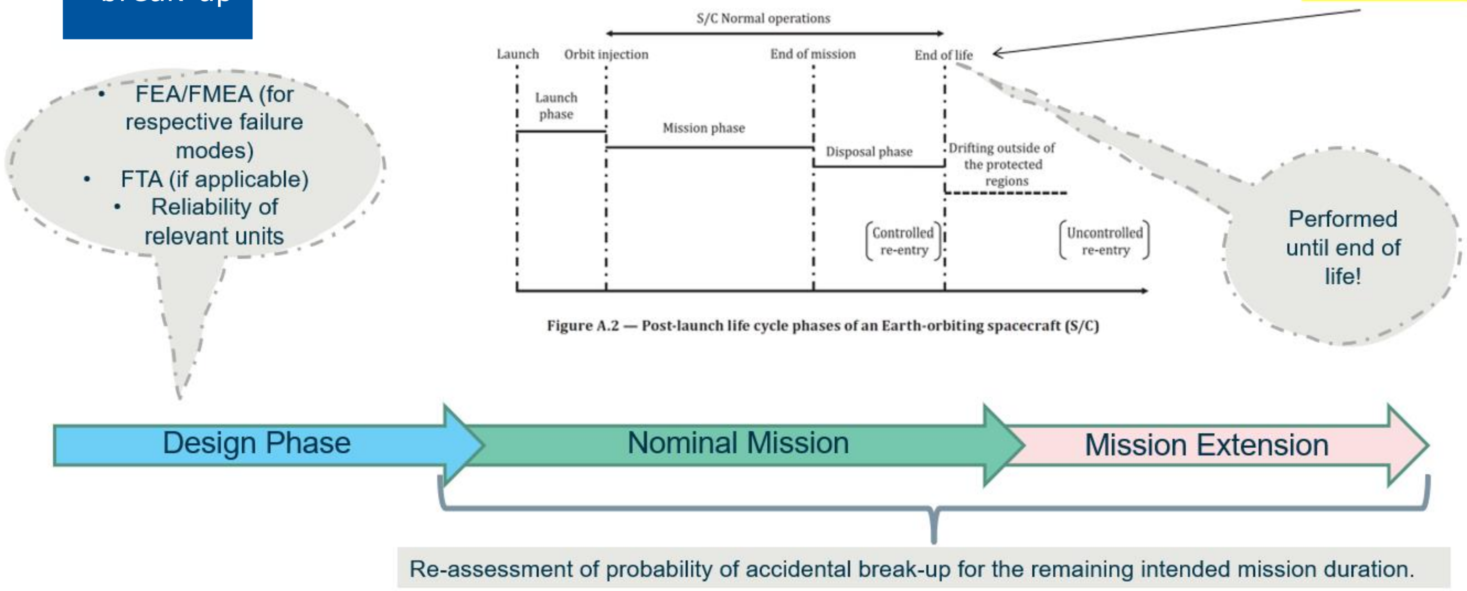


Figure A.2 — Post-launch life cycle phases of an Earth-orbiting spacecraft (S/C)

- FEA/FMEA (for respective failure modes)
- FTA (if applicable)
- Reliability of relevant units

Performed until end of life!

Re-assessment of probability of accidental break-up for the remaining intended mission duration.

Calculation of the accidental break-up probability with FTA:

- Start with the "accidental break-up" as the top event and trace back to identify contributing sub-events and failure modes.
- Assign probabilities to these events and align them with reliability predictions and FMECA findings.
- Calculate the overall probability of occurrence, ensuring accurate application of the mission duration.

Calculation of the accidental break-up probability with FMECA:

- Perform FMECA to identify components with stored energy that could cause accidental break-up.
- Pinpoint failure modes leading to accidental break-up, such as those related to high-pressure vessels, batteries, and tanks.
- Determine the likelihood of these failure modes occurring throughout the mission, correlating with existing reliability predictions.
- Calculate the cumulative probability of all identified failure modes (related to accidental break-up), ensuring the mission duration is accurately applied.

RAMS requirements from ESSB-ST-U-007

For CPO only

Calculation of the collision probability:
- FEA (only in early phases of design, in later phases it is covered by FTA)
- FTA having the top feared event as ‟ collision” -> used to assess the probability of occurrence of collision

- Mission **design**
- Mission analysis
- CONOPS
- **Design of contingencies** and performance analysis
- **FDIR**
- ACPL calculation algorithm
- **FMEA/FTA**
- **Reliability** (mission success)

Collision risk

FDIR
Operations
Reliability (as observed)

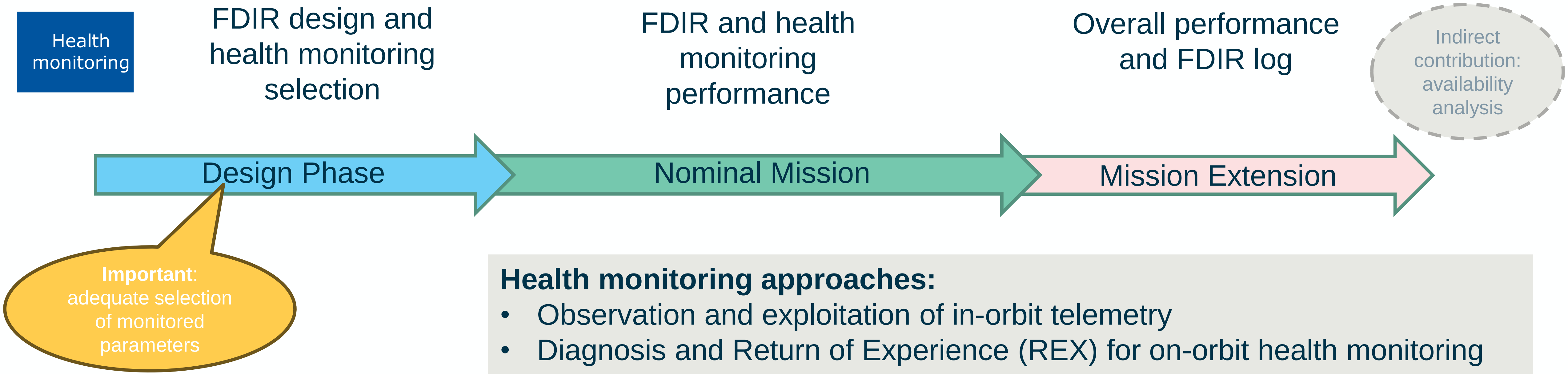
Design Phase

Nominal Mission

Collision probability calculation and requirement compliance proved with: mission analysis simulations and **FTA**

Fault Tree Analysis used to compute the probability of collision based on subsystem/unit/components failure rates and failure modes.

FDIR requirements from ESSB-ST-U-007



Health monitoring

FDIR design and health monitoring selection

FDIR and health monitoring performance

Overall performance and FDIR log

Indirect contribution: availability analysis

Design Phase

Nominal Mission

Mission Extension

Important: adequate selection of monitored parameters

Supporting Analyses:

- FDIR concept/design and implementation
- FEA and FMEA
- FTA (when relevant)
- HSIA

Health monitoring approaches:

- Observation and exploitation of in-orbit telemetry
- Diagnosis and Return of Experience (REX) for on-orbit health monitoring and failure rate computation using statistical methods and Bayesian techniques.
- Prognostics using stochastic models like linear evolution, lognormal law, and Weibull laws, as well as model-based and data trend monitoring approaches.
- Model-based models, derived from the analysis of the Physic of Failure of the unit and/or from the data of ground tests.
- Data trend monitoring (data-based approach).

Conclusions

- The presentation provides an analysis of **RAMS and FDIR requirements** essential for space debris mitigation and compliance demonstration in space missions.
- It emphasises the importance of incorporating RAMS and FDIR early in the mission design process to support initiatives like **Zero Debris for sustainable space operations**.
- The interplay between RAMS analyses, FDIR, and system engineering are highlighted to improve mission reliability and safety.
- Details and guidelines are offered on demonstrating compliance with part of the RAMS/FDIR requirements from **ESSB-ST-U-007**.
- The **forthcoming Handbook** will provide further details and examples for each requirement.
- The conclusion reinforces ESA's dedication to Space Debris Mitigation Regulation (SDMR), its role in international collaborations, and setting high compliance standards to **lead and inspire global SDM practices**.

The authors would like to express the deepest appreciation to all the members of the Space Debris Mitigation working group and the reviewers for their invaluable contributions to the standard and handbook. Their expertise, insights, and dedication have been instrumental in shaping the guidelines and ensuring their relevance and applicability.

Past, present and future activities

Validated reliability based models for EoL operations

Contractor(s): Thales Alenia Space (FR)		**ESA Budget:**	**400 K€**
ESA-TECQQD-SOW-013688	**YoC: 2021**	**TO: Radu, S. (TEC-QQD)**	
TRL	**Initial: 2**	**Achieved: 3**	**Target TRL: 9 by 2030**

Background and justification:

Spacecraft that survive their nominal mission lifetime are generally proposed for a mission extension to maximize their return on investment. The current criteria supporting mission extension decision, are mainly based on consumables (e.g. remaining propellant) and basic operational considerations. Nowadays there is an ever increasing pressure to comply with Space Debris Mitigation regulations since the population of space debris is expected to grow, especially because of expected large constellations. Some improvements are therefore needed in order to be able to dispose the satellite in a reliable manner and especially at the right time.

Objective(s):

The objectives were to develop, validate with in-orbit data and integrate improved reliability approaches enabling a more accurate quantitative risk assessment , as well as to define a concept of operation for the application of RAMS analyses and criteria for the EoL decision.

Achievements and status:

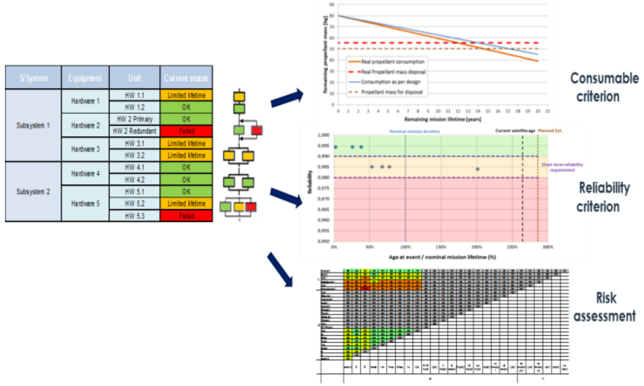
A generic reliability model has been implemented in Excel in order to support/apply the following approaches: the Health Monitoring on real operating conditions (e.g. temperature), the update of the model according to current performance and margins of units as well as the occurred failures; the return over experience; the prognostic and the Remaining Useful Lifetime (RUL) of units; and finally the enhanced risk assessment analyses. In addition, new RAMS criteria enabling a better risk-awareness decision on EoL of satellites have been evaluated and recommended: in particular a short term reliability criterion and some risk aspects.

Benefits:

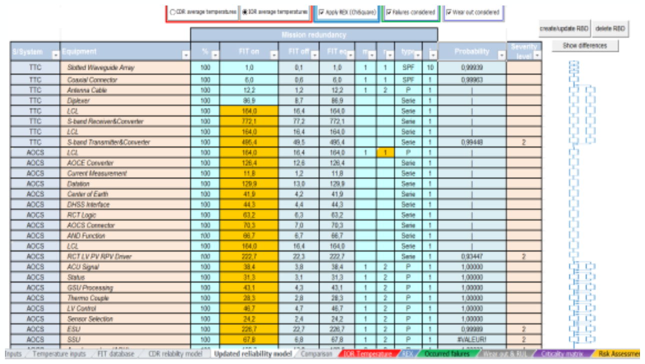
The proposed approaches and tool allow for a better risk-awareness decision on the End of Life and could ideally lead to a high Post Mission Disposal success rate in the future. This has been demonstrated also via the practical and operational use of these RAMS approaches for the End of Life review of real missions.

Next steps:

Future activities are needed and critical for solving the identified gaps within this study. Such as to apply these RAMS approaches on current and future novel satellites, to finalize the selection of the RAMS criteria, including their validation on previous/on-going missions; to further evaluate appropriate approaches for ‘New Space’ missions and constellations; and to further evaluate the prognostic approaches, and especially those based on data trend analysis which has been seen as very promising for EoL decision.



Overview of the decision-making process for the EoL



Generic reliability tool supporting End of Life decision

DetectAI

Contractor(s): Romanian InSpace Engineering SRL (RO)				**ESA Budget:**	**100,00 k€**
Programme & Reference		**Contract Number 4000137364/22/NL/AR/va**	**YoC: 2023**	**TO: Silvana Radu**	
TRL	**Initial: 1**	**Achieved: 2**	**Target TRL: 2 Date: Q4 2023**		

Background and justification:

- The growth and maturation of space technologies have led to more complex and ambitious space missions. This complexity necessitates advanced methods for monitoring and maintaining the integrity of spacecraft systems.
- While failure detection is already addressed through the Fault Detection Isolation and Recovery system, there is currently limited capability for on-board anomaly prediction. This gap in real-time assessment highlights the need for an activity to enhance predictive capabilities.

Objective(s):

- Perform necessary trade-offs with regards to methodologies and approaches in order to understand where Artificial Intelligence could be used for predicting and mitigating electronics/units failure and anomaly.
- Investigate best methods to develop failure detection, failure identification and potential recovery recommendations through the use of Neural Networks, for the identified electronic parts and/or units.

Achievements and status:

- Understanding of the benefits with regards to using AI/ML in comparison with conventional approaches with respect to RAMS.
- Understanding based, on the performed trade-offs, how prognostics based on data trend could help in prediction of degradation of electronics units.
- Understanding if an AI/ML approach for FDIR would contribute to a better availability of the System.

Benefits:

- Contribute to the Savoir FDIR Handbook, MB4SE project and other applicable/relevant standards.

Next steps:

- Establishing a partnership with a large constellation owner
- Implement and test the ML approach of FDIR
- Bring the ML FDIR to TRL 5/6 for at least 2 subsystems

Studies in preparation

- **TDE:** Framework for computation of probability of successful disposal
- **ARTES:** Digital twin for lifetime assessment of low Earth orbit telecom constellation satellites

To be published soon!

Thank you, Questions?